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Air Traffic Flow and the Congestion of the Skies:

Models, Insights, and Management Strategies for the Air Mobility Context

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Abstract

Air Traffic Flow and the Congestion of the Skies:

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With the potential to bypass congested urban road networks and take advantage of the openness of the sky, advanced air mobility (AAM) promises to provide a faster alternative mode for people and goods. However, AAM will also require a new paradigm for the movement of aircraft around an airspace network and may operate at densities of aircraft previously unseen in airspace and beyond the capabilities of existing air traffic management. Given the separation requirements between aircraft congestion may form on AAM airspace networks. Under such conditions managing air traffic flow effectively and mitigating congestion to improve the user and operator experience becomes very important.

In this dissertation traffic flow concepts developed from other modes are extended and adjusted to apply to aviation, specifically within the AAM context. This represents an important contribution because previous work on air traffic has generally focused on other topics than the macroscopic modeling and understanding of traffic flow behavior. Macroscopic air traffic flow models linking key traffic variables are established. A microscopic traffic simulator for AAM traffic is created and simulated results used to validate the macroscopic models. Sensitivity analyses to key operating parameters are performed to establish insights relating to traffic flow performance in the airspace. The effects of airspace restrictions are then studied at the local and network levels. A series of traffic flow experiments are performed in restricted airspace

structures and networks. After measuring traffic flow variables and other system performance metrics in the experiments traffic flow insights are then established.

The results highlight the importance of aircraft density and the conflict rate between aircraft when determining the traffic flow behavior and congestion. It is shown that higher densities of aircraft create more conflicts (predicted loss of separation events) between aircraft, which then negatively affect the average traveling speeds of aircraft and the throughput of the airspace. The macroscopic air traffic flow models are shown to have a predictive capability for air traffic flow conditions when compared with the simulated results. The models are also able to adjust to varying operating parameters such as separating minima between aircraft, maximum aircraft speeds, and heading restrictions in the airspace. The impacts of each of these parameters on air traffic flow behavior is discussed.

Airspace structures are shown to have an impact on the development of air traffic flow at the local level. The insights generated from the airspace structure experiments demonstrate three competing effects when considering the impact of structures. Airspace restrictions or structures may artificially raise the density of aircraft, may restrict the detour routing flexibility of aircraft, or may organize the airspace. These effects are not mutually exclusive but all affect at a macroscopic level how traffic flow behaves.

At the network level four general airspace network architectures are constructed and seven network performance metrics compared. The network performances reveal that there is no single best network architecture, rather each architecture represents trade-offs between priorities. The trade-offs between networks and the situations in which each network architecture performs the best are discussed.

The primary contribution of this research is the application of traffic flow concepts to the air traffic flow problem for the AAM context. Previous work in traffic flow offers a number of strategies and concepts that may be useful for air traffic flow. Meanwhile air traffic flow represents an interesting multi-dimensional extension to the traditional traffic flow models. Macroscopic air traffic flow models that extend and go beyond previous research in the area and created to describe the behavior of air traffic flow. The models provide a greater understanding of how air traffic flow may behave and congest. The macroscopic models are also sensitive to key AAM operating parameters, which gives them greater flexibility in application across contexts and creates interesting insights about traffic flow behavior. Ultimately the models may be used as part of a system to predict and monitor air traffic flow conditions and point towards management strategies. As one example, the air traffic flow models provide a reliable means for estimating both aircraft travel times and airspace capacities, each of which are of critical importance to both operators and users of the AAM system.

The dissertation also explores the interaction between airspace structures and air traffic flow. The traffic flow and congestion of airspace structures is illustrated through experiments. Comparisons among experiments illuminate a framework for thinking about the impacts of airspace restrictions and structures that will be useful when designing restricted airspace networks in urban areas. Impacts of network architecture on the operator and user experience are investigated experimentally. The benefits and drawbacks of various network architecture concepts are discussed and suggestions made that could help to improve the design of AAM networks from safety, efficiency, and external impacts perspectives.

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Chapter 1

1.1 Motivation

Congested urban roadway networks are a widely known and acknowledged problem in the modern world. The Federal Highway Administration estimates that drivers in the United States spend on average 47 hours in traffic congestion each year, representing a significant drain on the economy and livelihoods. Freight and goods delivery trucks likewise lose large amounts of time each year to traffic. Rather than continue to add to a congested road network, advanced air mobility (AAM) systems promise to enable users to bypass traffic and instead move through airspace above the urban area. Under this vision, people and goods could move freely around the urban area quickly and efficiently, saving hours of time for commuters and shippers alike. Furthermore, many proposed AAM systems utilize electric or alternative fuels configurations, promising to reduce vehicle emissions which are a problem for gas-powered cars and trucks.

Recent technological advances in batteries, aircraft design, communications, and aircraft power systems have combined to bring down small aircraft operating costs (Rajendran and Srinivas 2020). Reductions in costs have created opportunities in new markets for air mobility services such as cargo-carrying drones or passenger-carrying eVTOL vehicles. Collectively these areas are known as advanced air mobility (AAM) and offer cheaper and more efficient alternatives to current services. While AAM services are still in the development stage, estimates project that AAM could grow to serve tens or hundreds of thousands of trips daily (Alonso et al. 2017).

To serve such high demand within an urban area AAM operators will need to operate large fleets of aircraft in a finite area, placing a previously unimagined workload on airspace. Operations will need to account for conflicts with other AAM flights, obstacle avoidance from tall buildings or topographic features and existing airspace restrictions for other modes such as those near airports. Such operations are called urban air mobility (UAM), which also usually refers to an air-taxi service for passengers. The presence of so many aircraft operating simultaneously in a restrictive airspace and the need to enforce aircraft spacing requirements for safety purposes will create congestion issues for aircraft in the system. Congestion in airspace could increase travel times, reduce efficiency, and cause problems for operating schedules. Therefore an ability to understand, predict and ultimately manage congestion in airspace is critical.

1.2 Problem Statement

Demand predictions for AAM service in urban areas, or urban air mobility (UAM), includes estimates of up to tens of thousands of flights each day for mature UAM services (Bulusu 2019, Patterson et al. 2021), far surpassing current vehicle densities in airspace. The role of air traffic management is to control each of these flights such that they move through the airspace safely and efficiently. Safety of vehicles is assured through several mechanisms, including airspace restrictions and minimum separation requirements between pairs of aircraft. In addition to avoiding other AAM aircraft, flights will need to maneuver around obstacles such as buildings and other airspace restrictions in urban areas. The projected high level of demand placed on airspace coupled with the limited and restricted amount of airspace over an urban area and the need to separate vehicles will make air traffic management a critical component of AAM service. In order to avoid congestion within airspace and optimize the flow of aircraft through the system it is necessary to develop a better understanding of air traffic flow.

The work in this dissertation focuses on understanding air traffic flow at the macroscopic scale. Traffic flow is generally studied at either the microscopic (individual vehicles) or macroscopic (groups of vehicles across large spaces) scale, with work at the mesoscopic scale blending the two. With the aim of ultimately assisting AAM services to plan and manage high-density services, air traffic flow is studied at the macroscopic level because it better allows for management of the whole network of airspace. The drawback of focusing on the macroscopic scale is that the models can only predict the traffic experience of a group of aircraft or sector of airspace, and the actual experience of individual aircraft may differ.

An improved theoretical understanding of the macroscopic air traffic flow offers many benefits to the planning and operation of an AAM service. These benefits include creating a predictive capability for future traffic conditions within airspace, a framework for evaluating traffic flow under varying assumptions or operational parameters in the AAM context and a method for identifying a capacity of airspace that is tied to maximum throughput.

Previous work in air traffic management (ATM) and air traffic flow management (ATFM) have only addressed the congestion problem in various limited fashions (see section 2.7). Additionally, much of the previous work is not well-suited to the AAM context, which envisions much higher-densities, greater navigational freedom within sectors of airspace, and a high degree of automation once the technology reaches maturity. Since high densities of aircraft and traffic congestion will be especially relevant to long-term, mature AAM operations, this dissertation will focus on the mature state.

Additionally, airspace restrictions and structures add complexity to the problem by adding local airspace geometry and traffic directionality to the contextual factors impacting air traffic flow. Airspace restrictions may be used to limit the available airspace, or create layers or corridors of airspace, with each form of airspace structure affecting air traffic in different ways. How the varying geometry of the airspace interacts with the air traffic flow is only beginning to be understood (see section 2.8). However, this interaction figures to have a large impact on the experienced air traffic within the system, especially in high-density urban airspaces.

In this work a better understanding of air traffic flow specifically for the AAM context will be developed. Initially macroscopic models of air traffic flow will be developed that can explain the roles of vehicle and context parameters in air traffic flow and predict air traffic measures at a given density. The impacts of key operational parameters on air traffic flow will be explored in detail. Then the role of airspace restrictions will be examined. Airspace restrictions can serve both as safety and separation methods or as traffic improvement methods, and the effects of airspace restrictions will be studied at both the local and network levels.

1.3 Research Questions and Approaches

This dissertation will encompass a broad range of air traffic flow research questions, including a mixture of methodological questions for modeling AAM service and practically-focused insights arising from the models developed. The project can be viewed as two distinct areas of inter-related research questions, however the insights provided from each area are useful to consider in the other area and across AAM service more broadly. In generalized terms the three key research questions for this project are: 1) how can we macroscopically model air traffic flow and use these models to predict air traffic flow behavior in a given context, and 2) how do airspace restrictions impact air traffic flow at the local level and at the network level. Each of the next two sections looks more closely at the motivation of each of these general research questions and expands them with more specific questions and objectives. The research approach and methodologies to investigate these research questions are then organized in the following section, with expected research outcomes in the section after that.

1. How can we model air traffic flow and use these models to predict air traffic flow behavior in a given context?
    a. How can high-density air traffic flow be macroscopically modelled?

Traditionally traffic flows of aircraft have been either medium density operations that are highly-restricted by ATC and well-defined flight paths, or low density operations with fewer restrictions. AAM service, however, will provide greater mobility in airspace at a much higher density of vehicles. At the proposed density of hundreds or thousands of flights per day in a restricted area, more flexible and detailed models of air traffic flows are needed to understand how AAM traffic will behave and how to more effectively manage the AAM operational system. For example, what impacts do the number of vehicles in the system (a proxy of density) have on the number of conflicts encountered, and the average speeds of the vehicles? Based on these speeds and densities, how is the flow rate of traffic through the system impacted? In order to answer these questions, the first research objective is to develop theoretical air traffic flow models that can describe these relationships.

b. How do various operational parameters affect air traffic flow?

AAM service does not refer to a uniform use case with pre-defined and set operational parameters, but an array of use cases with diverse potential parameters and contexts. Therefore, it is important that the air traffic flow models answer the question: how do operational parameters affect traffic flow? The theoretical models will be developed with four operational parameters in mind: vehicle spacing requirements, vehicle speeds, conflict resolution systems and airspace structures. Changing any combination of these parameters would change how air traffic flow behaves and these changes will be studied. For a given set of parameters the traffic flow models can predict air traffic flow behavior and illuminate the trade-offs made due to operational decisions about these parameters.

c. How do the air traffic flow measures and operational parameters affect vehicle travel times and airspace capacity?

Key performance metrics for AAM service such as maximum vehicle throughput and travel times are also important to consider for AAM operators and planners because they better reflect the overall performance and output capabilities of the system. Therefore, the air traffic flow models will be extended to study how air traffic flow affects vehicle travel times and airspace capacity across varied operational parameters. A numerical analysis will use the air traffic flow models in a demonstration of how operational parameters affect these outputs. These results will explain the importance of air traffic flow management in direct user-experience and throughput terms.

d. How can we use simulation to validate these air traffic flow models?

It is insufficient to merely develop theoretical models without providing evidence in support of their modelling accuracy. However, as AAM service is still in its early stages of implementation there are no instances of high-density operations from which traffic flow behavior can be studied. Therefore, the theoretical models developed herein will be validated using a microscopic simulation of AAM traffic flow. The author will develop a simulator that can simulate the movement of vehicles and their interactions. Measurements of the traffic flow of vehicles within the simulation will be taken and analyzed. The simulated results will provide a useful check of the theoretical models and confidence in the use of the theoretical models in future work.

2. How do airspace restrictions impact air traffic flow at the local level and at the network level?

The air traffic flow models developed will provide a better understanding of management of air traffic, but there are airspace restrictions to be considered as well. Much of the expected demand for AAM is within urban areas for passenger or freight service, and these areas have numerous airspace restrictions that AAM service must work around. Proposed concepts of operation for AAM service include a network of corridors (see section 2.2), and this style of airspace will be studied. Vertiport locations will likely involve restricted airspace, and the impacts of such sporadically placed airspace restrictions on air traffic flow should be considered. Lastly AAM planners and operators may introduce new airspace restrictions and structures to organize airspace and reduce conflicts between aircraft, introducing a need for understanding the network level impacts of these structures.

    a. How do corridors of airspace impact air traffic flow at the local level?

Airspace restrictions will also affect the behavior of air traffic flow by impacting how the aircraft move through the airspace and how they interact with each other. The effects of airspace restrictions on air traffic flow at a local level will therefore by closely studied, beginning with corridor airspaces, which are commonly proposed structures for AAM service. Aircraft will be simulated moving through restricted corridor airspaces and the traffic flow patterns will be observed. The experiments will incorporate varying traffic directionality and structure shape in and near corridors and intersections of corridors. Not all airspace structures may impact traffic flow in the same ways, and therefore analyses will be developed that indicate these differences. Based upon the analysis insights will be generated that comprise a framework for thinking about the effects of corridor structures.

b. What is the impact of sporadic airspace restrictions on air traffic flow?

Not all airspace restrictions involve structuring AAM traffic into corridors. Many existing restrictions represent volumes of airspace that are either denied to AAM traffic or may be conditionally usable. These restrictions may be more sporadically placed across an urban area. For example, an urban area may incorporate smaller restricted airspaces surrounding buildings and obstacles as well as vertiports, with each of these airspaces denied to through traffic. While the impact of sporadic restrictions may not be as large compared with more systematic restrictions such as corridors, there is still a degree of impact on air traffic flow. This impact is explored. Additionally, insights about the trade-off between the amount of restricted airspace and the behavior of traffic flow can be drawn.

c. How can AAM air traffic flow be modelled at a network level?

While understanding airspace restrictions at a local level is important, understanding their effects on the network is important as well. Air traffic on a network of restricted corridors of airspace will behave differently from an unstructured network, for example. To test these effects and study the trade-offs made when planning for different network shapes, air traffic flow experiments are constructed for four different networks. Each of the four networks is simulated and seven different key performance metrics calculated. The performance metrics are then compared with each other at varying system densities to produce findings that indicate the relative strengths and weaknesses of different network architectures.

1.4 Contributions of this Research

Given the broad range of research questions, there are a number of contributions from this research. Developing air traffic flow models and using them to gain an improved understanding of AAM traffic in different airspace structures is a primary contribution of this research. And the air traffic flow models are subsequently used in an air traffic flow management problem to improve results. A point-by-point list of contributions of this dissertation is provided below.

- The overarching contribution of this work is in how it relates the concepts of traffic flow to air traffic, with the air mobility context specifically in mind. Previous work on air traffic management in aviation has largely focused on the existing airspace model in which aircraft are controlled by ATC systems and restricted to specific paths and sectors of airspace. Under these procedures the concepts of traffic flow have largely been limited to the margins of the air traffic management field, because of the low-density, high-restriction nature of the airspace. Advanced air mobility will necessitate entirely new procedures for aircraft moving through airspace, at much higher densities of aircraft in the airspace than have existed before. With such high densities airspace can become congested, imposing large negative costs to travel times and throughputs on the airspace, as this dissertation shows repeatedly. To manage this congestion concepts of traffic flow developed in other modes are applied and then further developed for the aviation context. This opens up new avenues for research and for understanding and managing the problems of air traffic. Air traffic and managing the aircraft on the system can now be viewed as traffic flow problems. Accordingly strategies for understanding and managing traffic flow can be applied to air traffic as well with the appropriate adjustments and considerations.
- More specifically, this dissertation develops macroscopic traffic flow models that relate aircraft density, conflicts, actual and effective speeds, and flow rate through airspace.

These relationships are developed around several straightforward concepts. The first is that higher vehicle density in airspace will create more conflicts because the expected number of trajectory intersections (conflicts) for each vehicle will increase if there are more vehicles in the airspace simultaneously. The second concept is that resolving these conflicts will reduce vehicle speed because some form of detour is needed by one or more aircraft. The third key concept arises from the fundamental identity, which is that vehicle speeds impact flow rate (or throughput). These concepts tie together the key traffic flow measures by indicating that density creates conflicts, conflicts reduce speeds, and speeds impact flow rates. The author is aware of only limited work on macroscopic air traffic flow models, and this dissertation improves on that work by incorporating the behavior of vehicle speeds in the models and by providing a more robust framework for explaining the behavior or air traffic flow.

- While the macroscopic air traffic flow models are more complete, they are also more flexible, in that they directly incorporate the impacts of operational parameters in the models. The effects of operational parameters such as spacing requirements, vehicle speeds, and heading restrictions are studied and insights for AAM operators and planners provided. These insights reveal a set of trade-offs made by operators when setting the operational context for AAM service, and optimizing these trade-offs for the desired policy goals can be beneficial to services.
- By using the air traffic flow models developed here it is also possible to obtain estimates of travel times and airspace capacity through airspace. These values are important for operators to consider when managing traffic flow. Additionally, the airspace capacities defined in this work are based on the maximum flow rate and a critical density. In

previous work airspaces capacities have been defined based upon either the maximum number of aircraft manageable by ATC (Vascik et al. 2018, Bulusu 2019) or maximum density before gridlock (Jardin 2004, Sunil et al. 2018a). Both of these methods have their shortcomings, specifically neither of them is based upon maximizing the throughput. By using the critical densities found through the air traffic flow models, flow rates through airspace can be optimized effectively.

- The second key research question pertains to the impacts of airspace restrictions on local traffic flow, which this dissertation examines. Two categories of airspace restrictions that are specifically used include corridor restrictions and sporadic restrictions. Since airspace restrictions in an urban area are a common challenge for AAM services, understanding how traffic flow will be impacted by restrictions is an important consideration. Previous literature has touched upon the effects of airspace structures, although it has not delved into the specific impacts on traffic flow. This work provides insights and a framework for thinking about how airspace restrictions impact traffic flow.
- Impacts of network architecture on AAM services are studied as well. This work specifically studies the traffic flow developed through several types of networks and develops findings from these. The results indicate that different network structures have varying strengths and weaknesses and are of specific interest to AAM planners who are developing an airspace network architecture for services. The information could be used to create or choose more efficient network forms.

1.5 Organization

This has been **Chapter 1**, which introduces the topic and problem, and explains the research questions and contributions that define this dissertation. The remainder of the work is organized as follows. **Chapter 2** reviews the existing concepts for AAM services that are relevant for this work. It then surveys the research previously done on related topics for this dissertation and identifies some of the areas that this dissertation improves. **Chapter 3** discusses the measurement of air traffic flow variables and the construction of the AAM vehicle simulator. **Chapter 4** introduces the conflict probability model used as a starting point for the air traffic flow models. It then develops the air traffic flow models and explores their ramifications considering variable operational parameters before providing results from scenarios that validate the air traffic flow models. **Chapter 5** creates simulation experiments of restricted airspace and studies the local impacts of restrictions on air traffic flow. **Chapter 6** defines four different network architectures that incorporate differing airspace structures. Each of the networks is simulated and key performance metrics measured to explore the benefits of each. **Chapter 7** summarizes the key takeaways from the preceding chapters and provides concluding remarks.

Chapter 2

In this chapter the relevant background for this thesis will be reviewed. This task includes discussing the state of the AAM industry, exploring the visions for the future of AAM service outlined by government agencies and others, and reviewing the academic literature relevant to modeling air traffic flow. The academic literature reviewed here includes topics such as simulation of aircraft, conflict prediction and resolution, air traffic flow management, airspace restrictions. Connections between the academic literature and this work will also be stated to provide a reader with a clearer view of how this work builds upon previous work and where it creates novel contributions.

2.1 State of the AAM Industry

Advanced air mobility (AAM) is a broad term meant to capture a range of emerging aviation modes that utilize newer technologies and smaller vehicle configurations. While AAM is too diverse to speak in absolutes, a few generalizations can be made. AAM vehicles are in general smaller aircraft utilizing alternative fuels (electric or hydrogen) to accomplish short range missions. Many, but not all, AAM vehicles have vertical take-off and landing (VTOL) capabilities to allow them to operate without the need for a large runway. Furthermore, many, but not all, AAM vehicles utilize rotors for propulsion and are designed to fly at lower altitudes and slower speeds than existing commercial jets. The major anticipated AAM use cases include automated, cargo-carrying drones, and passenger-carrying aircraft (often referred to as urban air mobility, or UAM). Other potential use cases include agriculture, emergency transport, military uses, and infrastructure inspection. The work in this dissertation is applicable in a broad sense to all aircraft, but is primarily aimed at AAM services, and specifically at passenger and freight flights in urban areas (UAM), which are more likely to operate at high densities of operations than other use cases.

AAM services are commonly envisioned as electric-powered VTOL aircraft (eVTOLs) moving goods and people on short-range (less than 150 miles), intra-urban trips that would otherwise face lengthy delays from congestion on road networks (Alonso et al. 2017). By utilizing available airspace and aircraft speeds it is anticipated that there could be significant travel time savings on long intra-urban trips. In the past a number of large cities have seen air taxi services operated by helicopters, but these services suffered from high costs and noise levels, as well as safety difficulties. New AAM vehicle configurations will increase flying efficiency and reduce noise levels to alleviate these concerns. Previous air taxi services similar to UAM made use of fixed-location helipads for pick-up and drop-off locations, and at least in the beginning UAM service will as well. A network of vertiport locations will be operated around the city, which will provide the infrastructure needed for the aircraft to take-off and land as well gathering points for passengers. There are currently few to no UAM services in operation, the services that are operating largely use traditional helicopters on small networks.

With AAM services still under development, there are numerous challenges standing in the way of implementation and mass adoption. Vascik et al. (2020) outlined many of these challenges including the development of an unmanned aircraft system traffic management system (UTM), definition of airspace restrictions, in-flight safety procedures, community acceptance, communication and navigational challenges, staffing requirements, air traffic flow management (ATFM), and delay assignment or trajectory based operations (TBO) for managing conflicts in airspace. This dissertation works on several of these challenges. The primary contribution is within air traffic flow management, while drawing upon and discussing UTM, airspace restrictions, and delay assignment and TBO.

2.2 Concepts of Operation

Several government agencies and others both in the United States and abroad have developed Concepts of Operation (“ConOps”) to provide a framework for how AAM service could look. These documents have focused mostly but not exclusively on UAM, or an air taxi service as opposed to other uses. NASA has been a key player in producing several ConOps documents and other similar work. In a 2014 precursor to an air mobility concept NASA explored a “zip aviation” concept that would use small, fixed-wing rental aircraft for intra-urban passenger trips to cut travel times (Moore et al. 2014). This study identified early on that short range flights could be used to cut travel times in an urban area.

Working for NASA, Johnson and Larrow (2020) outlined key concepts for unmanned aircraft system traffic management (UTM), including the continued use of minimum separation requirements between aircraft, a UTM system separate from but complementary to traditional air traffic control (ATC), performance and equipment requirements for use of UTM, and roles for UAS service suppliers (USS), which will provide key flight information to AAM operators. They also outlined a conflict management model based on three levels: strategic conflict management, tactical conflict management through aircraft separation, and emergency collision avoidance when tactical conflict resolution fails. A number of these concepts are important assumptions used in this work, the biggest of which are separation requirements between aircraft and the three layers of conflict management. Separation requirements between aircraft are a key component in the conflict prediction and air traffic flow models. The work also identifies roles for both strategic and tactical conflict avoidance systems. Tactical conflict avoidance is assumed in this work and the accompanying simulations as aircraft identify and resolve conflicts while in flight.

Separating aircraft in a safe and efficient manner is a key challenge for UTM. In general there are two systems for separating aircraft: assign large volumes of airspace with defined boundaries to a single aircraft or impose smaller separation minima between aircraft in the same airspace (Cotton and Wing 2018). In the short term or for certain types of missions such as low altitude package delivery the first method may be used. However, for higher demands on the airspace assigning sections to a single aircraft may be inefficient. Instead, separation minima between aircraft may be used, with conflict detection and resolution systems in place to ensure the separation minima. This system resembles the current national airspace system, which uses horizontal and vertical separation requirements. For example, one commercial aircraft may need to be separated from another by at least 5 nautical miles horizontally or 1000 ft vertically. Cotton (2019) proposed a method for determining various separation minima between UAM vehicles and other forms of aircraft based upon these concepts. Geister and Korn (2018) recognized that the current separation minima form a cylinder of restricted airspace around each aircraft, and instead recommended a combination of horizontal and vertical components to form a restricted ellipsoid around each aircraft. This form of separation minima would separate aircraft by a uniform amount of time. Minimum separation requirements are assumed in this dissertation, because they operate at the higher densities envisioned by this work. Furthermore an ellipsoidal separation minimum shape is used when detecting and resolving conflicts.

In May of 2020 NASA published a concept of operations for UAM service (Price et al. 2020) which categorized the development of UAM service into 6 stages, ranging from aircraft testing and certification in UML-1 up to high-density, widespread, automated UAM operations for UML-6. Automation of aircraft would be introduced across these phases and airspace configurations would be developed accordingly. The authors suggested that drone operations involving goods delivery might operate below 400 ft AGL, while UAM operations might be confined to 3000 ft AGL and less. Initially UAM operations would occur within specific and controlled corridors during UML-2, but as UML-4 and later was reached, the airspace configurations would be adjusted to allow ubiquitous operation of UAM vehicles throughout and urban area.

In June of 2020, the FAA, working with NASA, published a “UAM ConOps Version 1.0” (FAA 2020). This document provided a vision for early UAM service within the United States that could serve as a common reference point. The key contribution of this document was the prescription of “UAM corridors”, or corridors of airspace through other airspace classes designated for UAM use. While within these corridors the vehicles would use UAM specific procedures, although UAM vehicles could leave these corridors and revert to using the relevant local class of airspace. Corridors are envisioned to connect vertiports directly, creating a point-to-point network. The FAA may also intervene with a demand capacity balancing (DCB) system within the corridors, again highlighting a role for network-level traffic management of UAM. Initially the UAM vehicles are expected to be piloted and follow pre-specified tracks within the corridors, restricting their freedom of movement. With these restrictions in mind, the traffic flow of UAM vehicles through restricted corridors is studied closely and compared with other possible airspace and network structures.

Conceptualization of UAM service has happened in Europe as well, where EUROCONTROL has published several documents with proposed concepts of operation (Hately et al. 2019, SESAR 2020). Within these documents and others, U-space is commonly used to refer to airspace designated for use by AAM systems. This U-space would primarily occupy low-altitude airspaces and would have separate rules and procedures for the unmanned flights within it. EUROCONTROL proposes three new types of airspace for U-space in its ConOps document: Class X, Class Y, and Class Z. Each of these classes has varying requirements for unmanned aircraft within them, but in general class X airspace is for sparsely populated areas and offers no assistance with conflict resolution to aircraft. Class Y is for higher risk areas and would provide pre-flight strategic deconfliction for aircraft, while class Z would govern the highest-risk areas and areas near major airports, where both pre-flight and in-flight tactical deconfliction services would be offered. This document demonstrates to a greater extent how mature UTM could operate using both system-wide deconfliction and on-board deconfliction for each aircraft. It envisions a great degree of flexibility in navigation for AAM services, much more so than pre-specified AAM corridors. Navigation and deconfliction services would be supplied as services within the system by a network of service providers (USSPs).

For high-density systems with large numbers of simultaneous operations, and considering communication challenges, a UTM system may sectorize the airspace into smaller volumes that can be controlled locally. Bharadwaj et al. (2021) and NUAIR (2021) both propose a decentralized system of UTM in which vertiports control the airspace surrounding them. A decentralized system offers advantages when tracking, deconflicting, and communicating with aircraft, while a system sectorized by vertiport would allow vertiports to efficiently manage the air traffic in a way that cooperates with landing and take-off needs. The concept of sectorizing airspace and managing the traffic locally is also a common assumption in ATFM works (Bertsimas and Gupta 2016, Balakrishnan and Chandran 2017, Haddad et al. 2021). This dissertation similarly models the traffic within smaller defined airspaces that are envisioned as part of a larger system.

Other work by Airbus (Balakrishnan et al. 2018) highlighted four key types of aircraft routing to consider for AAM service: basic flight, free route, corridors, and fixed route. Basic flight would allow aircraft to fly their own chosen route and have each aircraft ensure separation from other aircraft. Free route would also allow any routes for aircraft so long as they coordinate with the UTM system, which would also help with deconfliction. Corridors would restrict AAM aircraft to defined airspaces, but aircraft would have some routing flexibility within these airspaces. Fixed route would prescribe set paths for aircraft to follow without any routing flexibility. Each of these routing systems has been considered for this dissertation, and comparisons between them at both a local and network level are made to help policy makers consider what airspace structures are most suitable under different conditions.

Based on these described concept of operations documents and others provided in the references list (Kohlman et al. 2019, Patterson et al. 2018), a number of assumptions about AAM service have been made for this dissertation. The major assumptions made are summarized here: that AAM aircraft will in the future operate in airspaces with high densities of operations, that aircraft will need to maintain a specific separation distance from each other, and that deconfliction at both the network and local levels are needed to maintain these separations. AAM vehicles will take off and land at specific vertiports that are built for these vehicles. AAM service will in general operate in low altitudes below a few thousand feet, and that passenger service will operate above 400 ft AGL with delivery drones beneath this altitude. Varying airspace structures such as fixed-routes, corridors, and unrestricted airspaces will comprise AAM networks, with earlier AAM service defining more restricted airspace for use that is expanded as the maturity level increases.

2.3 Demand Analyses and Predictions for Air Taxi

Some recent literature has attempted to estimate a level of demand for AAM service, specifically looking at the air taxi service for UAM. Since there is no current service to study, these works have generally paired theoretical UAM service metrics with existing car metrics. Key metrics considered include travel time savings, waiting time, cost, and access time. Demand predictions from these studies indicate that demand on limited networks in the short term could be low or moderate. But with an advanced system and larger networks in the intermediate-to-long term UAM levels of service could outpace cars for many trips, paving the way for much higher demand levels.

In a study for NASA Alonso et al. (2017) constructed a simulation of a UAM system within the Bay Area. A network of vertiports was chosen to accommodate long-distance commuters in the region and large (up to 30 passengers) aircraft were operated in restricted corridors between vertiports in a point to point network. By considering the access time, waiting time, and travel time of potential users to equivalent car trips the authors arrived at an estimate for UAM which considered a demand of up to 30,000 passengers daily in the region by the end of the 2020s.

Uber Elevate (2016) in a white paper studied the travel time savings for a UAM service relative to long distance ridehailing trips. By comparing hypothetical access and travel times with observed ground times it was estimated that 60% of such trips in Los Angeles could save at least 40% of their travel time. Such a statistic suggests that UAM service would be extremely competitive with car trips for longer distance commutes.

Bulusu and Sengupta (2020) performed an analysis that compared travel time, fuel costs and vehicle emissions from UAM with driving for both passenger service and freight service. The authors found that UAM compared favorably with driving for all three categories, and therefore would represent a very competitive mode that could change how cities operate. However, the analysis was not performed on an actual city network or with a set of trips, but instead was done by considering hypothetical trips using simplifying assumptions.

Rajendran and Shulman (2020) used a discrete event simulation of UAM service in New York City which considered passenger wait times to help determine an optimal fleet size of vehicles. Demand for the service was comprised of TNC trips within the region and it was found that the necessary waiting time for UAM service was a key determinant in travel time savings for UAM compared with an equivalent TNC trip.

While travel times may be competitive for UAM service, cost may be an issue. A Booz Allen Hamilton (2018) analysis compared UAM service on the basis of cost and estimated that in the long run UAM service may approach price levels similar to a ground taxi. While these prices would be reasonable for some, they could be too high for many to use on a consistent basis.

Each of these demand analyses compared UAM directly with relevant driving trips, and considered key measures such as travel time, access time, waiting time, and cost. The results showed that UAM service could be very competitive on the basis of time, opening up the potential for very high levels of demand if UAM becomes a replacement for even a portion of car commutes. However, the cost of service may be an issue, as it appears that UAM service may never reach cost levels as low as cars. Even if UAM service can capture a small portion of the urban transportation market though that could represent tens or hundreds of thousands of trips per day in larger urban areas. Managing the air traffic from even hundreds of trips may be an issue, and one that only grows more urgent as the service grows and matures.

2.4 Air Traffic Simulation

In the aviation field simulation has been used as an important tool for carrying out experiments. This is because real-world experiments are expensive and sometimes dangerous (Shah et al. 2005). In the AAM context there are currently no vehicles certified for commercial use, which prevents collection of real-world observations. Therefore many AAM concepts and experiments have been tested in simulations (Liu 2018, Bulusu 2019, Neto et al. 2019, Tereschenko et al. 2020, Zhao et al. 2019a, Xue et al. 2018). This work also makes use of simulation of AAM traffic flow and networks in order to validate air traffic flow models and test the local and broader impacts of airspace restrictions on air traffic flow.

There is a lengthy history of simulated experiments in aviation research, which is not delved into here. However several relevant works are discussed to provide some context of other simulations and their uses. Shah et al. (2005) provides an overview of a typical framework for simulations of air traffic, often used in research on air traffic management. The authors highlighted benefits of simulation for air traffic in that it allows quick and inexpensive testing of new concepts, albeit at a lower fidelity than real-world experiments. Important pieces of aviation simulations include tracking of aircraft positions within airspace and an agent-based decision process that reflects limited information, real-world decision making.

Sun et al. (2020) developed the aircraft simulation tool BlueSky for conventional, fixed-wing commercial aircraft. This open-source simulation tool is primarily aimed at air traffic management experiments and uses detailed models of individual aircraft performance to accurately model the movement of aircraft within airspace. This simulator has been used in other studies of air traffic management (Tereschenko et al. 2020, Ribeiro et al. 2020).

There have also been a number of private simulators developed by researchers specific to the AAM context. Xue et al. (2018) developed a high-fidelity simulation of AAM aircraft for NASA based on the six-degrees-of-freedom concept. Six-degrees-of-freedom simulations track the orientation angles and forces acting on aircraft in addition to the positions of aircraft to provide a realistic representation of the aircraft trajectory (Josselson 1997). However the high accuracy of these trajectories comes at the cost of computational efficiency, as most of these simulations can handle only a few dozen aircraft simultaneously.

Neto et al. (2019) wrote about the development of a simplified simulator of AAM traffic, which would consider aircraft positions, speeds and accelerations but not the specific forces and angles affecting aircraft. The flights were organized into a number of pre-assigned flight levels. The authors determined that this simulator could be useful in studies of air traffic management for AAM. The study also included some limited simulations of aircraft operating at several different altitude levels with strategic, pre-flight deconfliction performed to ensure no conflicting trajectories between aircraft.

Bulusu (2019) also used a simplified simulator of drones to study airspace capacity in the San Francisco Bay Area. By considering all flights to occur at the same altitude level and to use a rules-based, vertical-detour-only conflict resolution system the author was able to simulated tens of thousands of aircraft simultaneously. A safety threshold based on the number of conflicts for nearby aircraft was determined and used to estimate airspace throughput capacity. The loss in efficiency due to detours, lost travel time, and extra fuel costs were also considered.

Also studied was the relative efficiency of using a speed-based versus a detour-based conflict resolution method.

An aircraft path-planning model was developed by Liu (2019). The paper aimed to create a model of aircraft motion that could coordinate and deconflict paths for aircraft within a 2D simulation, assuming that aircraft fly at the same flight level. This AAM simulator is notable for using a non-linear program to optimally resolve tactical conflicts for in-flight aircraft. The conflict resolution system also allows for combinations of both speed-based and detour-based solutions. The simulator was used to discuss the speed and heading efficiencies of aircraft during high-density operations, with the author noting that the flight efficiencies declined when densities peaked.

The simulator developed for use in this work (see chapter 3) draws concepts from numerous other simulators. The simulation uses a relatively simplified aircraft motion when planning trajectories on a rolling horizon. Conflicts between trajectories are detected using aircraft intent and resolved by individual aircraft without coordination. The conflict resolution algorithm uses a non-linear program with a similar approach to Liu (2019). While this simulation does not create a high-fidelity model of aircraft movement, it is generally sufficient to model the movement of aircraft for purposes of studying the macroscopic traffic flow. A similar simplification about altitudes is made to Neto et al. (2019), with aircraft grouped together on pre-assigned flight levels, but with detours off of those flight levels allowed. This simplification reflects the current national airspace system, where aircraft generally achieve a cruise altitude during flight and avoid deviating from it. Further details on how the traffic flow is measured within the simulation can be found in chapter 3.

2.5 Conflict Resolution

A key underpinning to air traffic is conflict detection and resolution (CD&R). When the trajectories of two or more aircraft intersect they must be adjusted so that the aircraft do not lose separation or even collide. A substantial amount of research has been done on conflict resolution between aircraft, which encompasses a plethora of methods and contexts. An excellent review and categorization of conflict detection and resolution methods was done by Ribeiro et al. (2020a). Important pieces of that review are summarized here.

Ribeiro et al. begins by discussing conflict detection methods. Detection methods for aircraft can be categorized into centralized or decentralized systems, with conflict detection either performed by one central infrastructure system or by aircraft in the airspace. Centralized conflict detection allows for greater coordination between aircraft and potentially a farther “look ahead” for aircraft but depends on reliable communications of conflicts with aircraft. Decentralized conflict detection does not require reliable communications but also lacks the coordination of a centralized system. In order to predict conflicts, the system must also predict future trajectories of aircraft, which is done either by extrapolating the aircraft’s current position and heading (state-based) or by checking the aircraft’s planned trajectory (intent-based) (Ribeiro et al. 2020b). The reliability of an aircraft’s future trajectory is also considered, with assumptions made about the probability of the aircraft traversing its planned trajectory or others.

Conflict resolution can also be performed using centralized or decentralized systems with the same benefits and drawbacks of conflict detection. Conflict resolution methods can include trajectory optimization (Liu 2019), heuristics, rules-based solutions (Mao et al. 2001, Stroe and Andrei 2016), or negotiated solutions. Trajectory optimization involves using an optimization model to identify the optimal trajectory adjustments for the conflicting aircraft, and the cost function can be adjusted to reflect policy priorities. Heuristic resolution can imitate optimization techniques but ultimately utilize rule-based methods to simplify the problem and shorten the computation time. Rules-based solutions involve conflicting aircraft following pre-defined procedures for handling conflicts. For example, the lower priority aircraft might always initially reduce speed to avoid a conflict before attempting a heading-detour of a fixed amount. Negotiated solutions occur when aircraft negotiate with each other to identify their priorities and the best solution for each.

Conflict resolution occurs along three dimensions: a heading change (aircraft detours horizontally), a speed adjustment (aircraft speeds up or slows down), or an altitude change (aircraft ascends or descends away from other aircraft). Trajectory adjustments in each dimension are useful in different contexts, often depending on the aircraft speeds, approach angle, and the geometry of the separation requirement between aircraft. In general altitude changes are avoided where possible by aircraft because they are both energy expensive and create discomfort for passengers.

Several studies have considered the relative benefits of a delay based conflict resolution or changes to the shape of the trajectory (trajectory based operations). Evans et al. (2021) considered whether it was better to strategically delay aircraft to avoid conflicts or to resolve those conflicts tactically with TBO. The authors concluded that for high levels of demand a tactical TBO resolution worked better because it significantly lessened the propagation of delays from previous conflicts. Liu and Hansen (2021) similarly studied a system of metering at an airport and determined that TBO could increase the efficiency of traffic while maintaining safety.

Different conflict resolution systems may be used for different levels of resolution, whether strategic, tactical, or collision avoidance. Pre-flight strategic resolutions could use a time-expensive optimization technique since solution time is not a priority. However, in-flight tactical resolutions might use a rules-based system because it takes less time to identify the solution. Flight schedule adjustments are one way to strategically deconflict trajectories, although this type of trajectory adjustment is not possible for tactical resolution. While altitude adjustments are generally avoided during strategic and tactical resolution, they may be necessary in case of an emergency collision avoidance.

The air traffic flow models and patterns explored in this dissertation make no assumption about the method of conflict detection or resolution, since the broad patterns will be applicable to all methods. However, different methods may have varying impacts on traffic flow. For example, a less efficient conflict resolution method might decrease the effective speed of aircraft more. These impacts are discussed where appropriate (see chapter 4). Furthermore, air traffic flow simulations are used commonly to examine patterns of traffic flow. The traffic flow simulation depends on a decentralized, intent-based conflict detection algorithm that allows each aircraft to check the planned trajectories of other nearby aircraft. A decentralized, trajectory optimization model is used for tactical conflict resolution, since it allows for the optimal combination of detour and speed adjustments for aircraft.

2.6 Conflict Probability and Reducing Conflicts in Airspace

Since conflict resolution is a key aspect of air traffic management, determining conflict probability is important to understanding and predicting air traffic behavior. The air traffic flow models in this work are built around first predicting the number of conflicts in the airspace, and then modeling how those conflicts impact the air traffic flow. Past research has modeled conflict probability between aircraft using a variety of methods, generally with the goal of determining the safety level of a system. Therefore, airspace systems that resulted in a higher conflict rate between aircraft are generally deemed to be undesirable, because it increases the risk of a collision, and at the least requires conflict resolution. The literature summarized here aims to provide a baseline understanding of what work has been done for conflict probabilities. The discussion then explores how conflict probabilities have been built upon in this work to draw conclusions about air traffic flow and airspace.

Mitici and Blom (2019) published a review of air traffic conflict probability models. These models include “in-crossing” models, Markov chain models, and Monte Carlo simulations. In-crossing models aim to find the probability that one aircraft crosses in front of another aircraft during a certain amount of time. The aircraft are considered to have volumes of airspace surrounding them that represent the spacing requirements and which other aircraft cannot enter. The probability that an aircraft flying on an independent trajectory would enter the separation volume surrounding another aircraft is determined to be the conflict probability. There are several ways of calculating this probability, but this dissertation uses adjustments to the gas law model. The gas law model likens aircraft to gas molecules and uses conflict rate equations initially developed for chemistry to define the conflict rate. Each aircraft and the spacing volume surrounding it are moving along its trajectory at a known speed. Therefore, the aircraft could be said to “sweep” through a volume of airspace within a given amount of time. By calculating this volume of airspace that the aircraft moves through and multiplying it by the known density of airspace, it is possible to estimate a conflict rate for how many conflicts the aircraft would expect to encounter. A full explanation of this dissertation’s conflict rate model is provided in section 4.2.

Building off of the gas law model, Jardin (2004) determined separate conflict rate models for whether conflict resolution between aircraft was applied or not. The author determined that in high-density airspaces, resolving one conflict between aircraft increased the likelihood of other conflicts, since the detouring aircraft would be flying a longer route or spending more time in the air than initially. From this concept he proposed that at a certain point the “chain reaction” of conflict resolution causing more conflicts would accelerate and cause a rapid growth in the number of conflicts in airspace. To determine this point Jardin created a “domino effect parameter”, which represents how quickly the conflict rate increases due to conflict resolution. The point at which the conflict rate accelerated unsustainably was suggested as a marker for airspace capacity. A key concept established in this was the idea that conflicts increase non-linearly with the density of aircraft.

An in-depth look at using the domino effect parameter (DEP) to estimate airspace capacity was done by Sunil et al. (2018a). In this paper the authors established that the DEP could be estimated for an air traffic system by using observations of the number of conflicts with and without conflict resolution at lower densities. The DEP could then be used to estimate conflict rates at higher densities and suggest a density at which the conflicts would propagate uncontrollably. The authors also performed simulations to estimate the airspace capacity using the BlueSky simulator. The simulation results suggested that larger aircraft spacing requirements and vertical detours from conflict resolution created the largest acceleration in conflict rates.

Through the DEP conflict probabilities have been used as a means for estimating airspace capacity. Conflict rates have also been used to compare the effectiveness of different airspace concepts. Sunil et al. (2015) simulated the air traffic over a fictional urban area with four different airspace types. The airspaces tested included point-to-point flight corridors, a network of zones with restricted headings allowed in each zone, a layers concept in which aircraft are vertically separated into layers of airspace according to heading, and unstructured airspace in which aircraft can fly at any altitude along any flight path. By comparing the conflict rates observed in each airspace scenario, the authors concluded that the layers concept of grouping aircraft by heading into different altitude layers was the most successful at reducing the conflict rate. They suggested that this was because the similar headings of aircraft reduced the likelihood of conflicts but the layers also did not create artificially high local densities of aircraft that were observed by consolidating aircraft into zones or corridors.

In order to expand on the concept of grouping flights by similar headings (called “geovectoring” by the authors), Sunil et al. (2018b) published a paper investigating the conflict rate of aircraft in a geovectored airspace relative to unstructured airspace. The gas law conflict prediction model depends in part on the expected relative velocity between aircraft, and the authors proposed updating this relative velocity term for geovectored airspace to represent the increased similarity in headings of aircraft. Using this model and simulations the study demonstrated that geovectored airspace had a consistently lower conflict rate relative to unstructured airspace, which could be considered to increase the safety of flights. Furthermore, restricting the allowable headings in each layer to narrower ranges decreased the conflict rate. When considering the DEP method of estimating airspace capacity, geovectored airspace would be considered to have a higher airspace capacity than unstructured airspace.

Tereschenko et al. (2020) used conflict probabilities to work towards developing a theoretical traffic flow model for aviation. The authors of this study linked conflict probability to vehicle density using a gas law model. Relationships between a higher conflict rate and lower effective flow rates were formulated, which created a macroscopic fundamental diagram (MFD). Initial simulations were constructed in the BlueSky simulator to demonstrate the relationships between density, conflict rate, and flow rate. However, this traffic model was problematic because it assumed uniform and constant vehicle speeds, did not illustrate the direct relationships between vehicle parameters and traffic flow relationships, and offered only limited testing of the effect of vehicle spacing on traffic flow, with no exploration of the role of other factors in traffic flow. Furthermore, several terms in these models required calibration for each specific context, reducing their applicability for predictions. The work in this dissertation takes a similar approach in developing air traffic flow models, but ultimately goes beyond this work by explicitly considering the role of both actual and effective aircraft speeds and by modeling the effects of vehicle parameters on air traffic flow.

An important component in conflict prediction and air traffic flow is the tracking and prediction of future density of aircraft. Several papers (Shi-Garrier 2021, Zhao 2020) propose using machine learning models to predict future densities in airspace and to identify “hotspots” where air traffic could become congested. The algorithms proposed are generally based upon historical demand for each sector of airspace and the current state of the airspace. Use of these models could help improve estimation of conflicts and traffic congestion in the near future.

2.7 Air Traffic Flow Management

This dissertation is primarily concerned with air traffic flow: measuring it, predicting it, and managing it. Previous research has looked at managing air traffic flow in a limited fashion, sometimes in terms of strategically deconflicting airspace by delaying or routing aircraft away from congested airspaces. Menon et al. (2004a) proposed an Eulerian model, which decomposes airspace into discrete links on which the number of aircraft is tracked. The movement of aircraft from link to link is modeled according to the Lighthill-Witham-Richards (LWR) model of partial differential equations. The links are considered capacitated, and by adjusting the routing of aircraft over the links it is possible to manage the flow on each link such that no single link reaches or exceeds a set capacity. Chin et al. (2020) used such a link-based ATFM model to investigate the trade-offs between efficiency and fairness when assigning aircraft delays in order to comply with the link capacity requirements. Zhou et al. (2021) similarly considered a network of links for AAM vehicles, with each link representing a queue and utilizing queueing theory to model the throughput. Models in this style simplify airspace by decomposing it into links, which may be aligned with existing flight segments between waypoints in use by aircraft. However, the assumption that airspace is a series of links is not appropriate for flexible airspace types that allow aircraft more navigational freedom.

Bayen et al. (2006) developed simulations of commercial air routes in the United States using an Eulerian model and compared the results with observed flight data from those routes. They also proposed an optimization model for determining the optimal flow of aircraft on each link. Their results determined that an Eulerian model enabled automated control of the flight network for real-world scenarios which included high-density scenarios.

Work and Bayen (2008) further developed the optimization problem into linear and quadratic programs which prioritized both maximizing aircraft throughput and minimizing aircraft delays. The authors suggested that this method could be used by air traffic control to plan for and manage the flow of aircraft on routes. By optimizing the flows of aircraft it would be possible to make better use of airspace capacity in the face of high demand.

While work with Eulerian models has used links and the LWR model to optimize traffic on those links, other work has instead focused on decomposing airspace into sectors, which better reflects the multi-dimensionality of airspace. Menon et al. (2004b) created an automated method for decomposing airspace into sectors and tracking the density of aircraft across sectors. By modeling the routes of aircraft through sectors controllers could predict high demand and execute solutions to divert aircraft to other sectors. Tang et al. (2021) used a method of Voronoi diagrams to decompose airspace into a set of simple sectors. Each sector is considered to be capacitated and therefore an optimization model could be used to route aircraft through the sectors such that each sectir remained below capacity. Balakrishnan and Chandran (2017) presented an optimization program for solving the ATFM problem considering a set of trajectories linking origins and demands through a network of capacitated airspace sectors. Bertsimas and Gupta (2016) used an ATFM problem with capacitated sectors of airspace and airports to consider questions of fairness when assigning delays to aircraft. While these papers do better capture the dimensions of airspace and allow for modeling of unstructured or loosely restricted airspace, they lack sound modeling of the traffic within each sector, which would affect the travel times of aircraft and their schedule for movement from sector to sector.

The author is only aware of one paper (Haddad et al. 2021) that considers macroscopic air traffic flow models when solving the ATFM problem. In this study a network of airspace sectors was constructed, with traffic flow in each governed by its own macroscopic fundamental diagram. Traffic flow was managed in each sector by metering the transfer of aircraft from adjacent sectors to each airspace sector, effectively assigning delays to aircraft in order to keep each sector’s traffic flow in an uncongested state. By modeling macroscopic air traffic flow it is possible to effectively manage a much larger number of aircraft at higher densities and predict the impacts on traffic flow. This paper had a few limitations in that it did not consider the theoretical models behind air traffic flow, relying instead on simplified models with coefficients derived from a limited set of simulated results for one specific context. The work also did not allow aircraft to re-route off of their trajectory when facing a lengthy delay. Aircraft had no means to use less congested sectors in this model, which does not capture the full flexibility of the airspace system.

2.8 Airspace Restrictions

The second key question of this dissertation deals with how airspace restrictions impact air traffic flow. Airspace restrictions are an important consideration for UAM for several purposes, whether avoiding static obstacles and restricted airspace near airports or to create airspace structures that minimize the conflict rate between aircraft. Previous research in obstacle avoidance (Kim and Yoon 2020, Cho and Yoon 2021) has highlighted the importance of airspace restrictions for low-altitude vehicles near obstacles, which may be abundant in low-altitude urban airspace. Vascik et al. (2019) examined the airspace classifications and restrictions in the Bay Area and discussed the usable airspace for UAM within four scenarios of varying restrictions. Under their most restrictive scenario less than 50% of the airspace and population were accessible for UAM, primarily due to existing airspace restrictions around airports. And airspace restrictions have been proposed as a traffic management strategy (Sunil et al. 2015, Hoekstra et al. 2018, Neto et al. 2019, Balakrishnan et al. 2018). These restrictions aim to reduce the conflict rate of aircraft in airspace either through restricted zones, headings, or altitude layers.

Geofencing, or delineating geographic boundaries in airspace that must not be crossed by aircraft, is one commonly discussed method of restricting vehicles in airspace (Kim and Yoon 2020, Cho and Yoon 2021, Geister and Korn 2018, Stevens 2019). Geofences could be either permanent or temporary depending on the situation, and could also apply variably to different sets of aircraft.

Corridors of airspace or “keep-in” volumes involve a similar concept, except that aircraft are given a restricted set of usable airspace to navigate within. This form of restriction is especially likely for the early stages of UAM service because it allows for smaller, simpler, tightly controlled airspaces (FAA 2020). Within corridors AAM air traffic can be separated from other forms of aviation and from other AAM traffic flows. Badea et al. (2021) investigated conflict detection and resolution methods within corridors and found that corridors do decrease the number of conflicts, although their results on the distance traveled and efficiency were mixed. Zhao et al. (2019a) defined a simulation of AAM vehicles within a point-to-point network and a grid network of corridors. The conflict rate, throughput, and signal connectivity for communications were measured within the network.

A vertical restriction method is layered airspace, which separates the airspace into specific altitude levels which ensure vertical separation between aircraft or groups of aircraft (Hoekstra et al. 2018, Neto et al. 2019). Layered airspace takes advantage of the increased dimensionality of airspace, and can also be useful for separating aircraft that would otherwise be in conflict. Hoekstra et al. (2018) also proposed the concept of "geovectors", or zones of airspace restricted for the use of only aircraft within a specific heading range. The authors found that by grouping aircraft with similar headings together in this way (potentially on different altitude layers), the conflict rate between aircraft could be significantly reduced. Doole et al. (2021) also proposed a layering method, except for corridors of airspace that would operate above the existing road networks. The layers of airspace would separate traffic in different directions on the same corridor and intermediate "turning" layers between the main corridor layers of airspace would allow for aircraft at intersections to move from one corridor to another.

In this dissertation the author uses several shapes of keep-out airspace restrictions in order to study air traffic flow within each context. In chapter 5 simulated experiments in restricted airspace similar to Badea et al. (2021) and Zhao et al. (2019a) are conducted, except with a specific focus on air traffic flow and insights pertaining to it. Airspace restrictions are shown to have a large impact on air traffic flow by restricting or allowing the movement of aircraft in certain directions and certain areas. Furthermore, the impacts of restrictions are significant at both the local and network level, since airspace restrictions define how aircraft move around the network. Previous work with UAM networks includes Sunil et al. (2015) and Zhao et al. (2019a), each of which defined service networks that used airspace structures and measured the conflict rate and throughput of aircraft. Chapter 6 takes a similar approach and experiments with varying network architectures that use restricted airspace. This chapter expands previous efforts by incorporating a more holistic analysis of the traffic flow behavior and includes other key performance metrics such as travel times and distances. The behavior of traffic in the system and the outcomes across several key performance metrics are shown to be strongly related to the network architecture. In each of these chapters the airspace restrictions in place for each experiment or model are stated.

2.9 Vertiport Design, Management and Location

A key portion of the AAM system and a special case to consider for air traffic flow is vertiports and take-offs and landings. Aircraft must be able to take-off and land safely at vertiports, and traffic originating from and destined for a vertiport would ideally have easy access to a vertiport. Recent research has begun to look at these issues.

While designs of vertiports are still under development, it is possible to discuss several different vertiport orientations that impact operations at the vertiport. NUAIR (2021) defines three vertiport designs: single pad, hybrid, and linear process. A single pad design involves an aircraft landing, unloading, loading, and taking-off from the same pad. A hybrid design involves one take-off and landing pad and a separate staging area for unloading and loading which the aircraft is moved to on the ground. The linear process design has separate pads for take-off and landing and a separate staging area. Each of these designs offer a trade-off between space and efficiency.

Some recent work has begun to look at management of traffic near vertiports, it has largely been focused on the aircraft landing problem and optimizing the landing schedule (Pradeep and Wei 2018, Kleinbekman et al. 2018, Zhou et al. 2020). The assumptions made about operations near vertiports accordingly are varied. Pradeep and Wei (2018) and Zhou et al. (2020) formulated an aircraft landing problem for vertiports with a single landing pad. Therefore the goal is to schedule the arrival of aircraft as quickly as possible while considering varied battery states on the vehicles. A single approach path is assumed, which is a straight vertical descent from a point directly above the pad. Minimum safe trailing times between vehicles are included in the model, but impacts from other local aircraft not landing at the vertiport are ignored, implicitly assuming that vertiports are in airspace restricted only to arriving or departing aircraft.

Kleinbekman et al. (2018) detailed a more complex concept for vertiport traffic in their formulation of an eVTOL arrival scheduling algorithm. Each vertiport (again represented by a single landing pad) is given two arrival and two departure fixed flight paths. Each of these flight paths involves a “glide path” to and from the vertiport, incorporating both horizontal and vertical movement during climbing.

NUAIR (2021) proposed a similar configuration to Kleinbekman et al. with more details about operations. Each vertiport would exist at the center of two volumes: the Vertiport Operations Area (VOA) and the Vertiport Volume (VPV). The VOA would represent the outermost extent from the vertiport within which aircraft must coordinate with a service provider to provide information such as location and heading. The VPV would be an inner volume in which aircraft operations are controlled by the vertiport manager. An aircraft passing through the area could move across the VOA but cannot enter the VPV unless arriving or departing at that vertiport. Aircraft arriving at or departing from the vertiport would navigate through a defined series of fixes in the airspace to guide them, and these would be aligned over both a vertical and horizontal distance. This NUAIR model is notable because it imposes airspace restrictions. So even for an airspace system without any other restrictions, the vertiports themselves will bring some level of restriction to the AAM system. These restrictions should be accounted for in the study of traffic flow and are looked at as sporadic airspace restrictions in chapter 5.

Other recent work has begun to consider the most effective methods for locating vertiports around a network. This research on vertiport location can be generally grouped into two methods: a clustering based method and an optimization based method. Rajendran and Zack (2019) used a clustering approach to determine suitable vertiport locations in New York City. Using a filtered dataset of long distance TNC trips trip origins and destinations were clustered with preference given to minimizing user travel times. Based on the suggested clusters the authors computed the coverage of the network (origins and destinations within a mile of a vertiport).

Rath and Chow (2020), Daskilewicsz et al. (2018), Sharavani et al. (2017), and Venkatesh et al. (2020) each used an optimization technique to locate vertiports within an urban area. In general the city would be divided into smaller zones (such as census tracts) and mixed integer program would determine which zones to assign vertiports to in order to minimize total travel time. The optimization was usually done for a subset of the population of trips, such as taxi trips or high income solo driving trips. The flexibility of the cost function allows for consideration of other priorities when locating vertiports, such as favoring underserved communities or locations with strong potential for UAM adoption. These papers also include sensitivity analyses of the network size, demonstrating that the majority of demand can be reached with a handful of vertiports.

Chapter 3

A variety of air traffic flow studies comprise this dissertation. But before those studies can be performed, key pieces of methodology need to be developed. This chapter discusses the measurement of key air traffic flow variables and the setup of the AAM vehicle traffic simulator. The measurement of traffic flow variables is critical for accurately describing and studying conditions within the air traffic flow from a macroscopic perspective. These measurements are constructed by aggregating individual behavior of aircraft. Edie's definitions of density and flow rate, which were initially developed for ground-based modes (Edie 1965, Saberi and Mahmassani 2014, Saberi et al. 2014) are expanded here to cover the multidimensionality of aircraft trajectories. The focus on air traffic flow also relies heavily on a simulator of AAM vehicles and traffic flow. The simulator is used to validate air traffic flow models and study the effects of airspace restrictions on air traffic flow because of the lack of real-world operating contexts for generating observed data of AAM traffic flow. Therefore, it is important to use a simulator that accurately approximates the behavior of AAM vehicles in airspace. The setup of the simulator and key aspects of it are described in this chapter.

3.1 Assumptions

Given the complexity of the airspace system, the context under which AAM operations will occur, and uncertainty about the future shape of operations, it is necessary to make a number of assumptions about the space in the process of developing and testing models. These assumptions are included throughout the dissertation, but the major assumptions are also listed here for the reader's convenience. Each assumption is described, and alternatives and justification discussed.

Aircraft Capabilities

There are a number of assumptions made about the capabilities of aircraft active in the airspace. Aircraft are assumed to be eVTOL aircraft capable of vertical take-off and landing, meaning that they are capable of climbing or descending at a true vertical angle of attack. It was also assumed that, similar to a helicopter, these aircraft have no minimum speed in order to remain aloft, but could move slowly or not at all through the airspace. Under this assumption an aircraft choosing to stop and wait while congestion ahead of it clears is a viable alternative. While many AAM configurations do have these capabilities (Bacchini and Cestino 2019), they are not ubiquitous. Other designs closer to fixed-wing aircraft exist that would require forward flight in some form to generate lift. For these aircraft the concept of a dense airspace producing more conflicts would still hold, however it would be more difficult to resolve conflicts and the detours required in conflict resolution may generate conflicts at an even higher rate than aircraft under these assumptions (Jardin 2004).

Aircraft are also assumed to have an abundance of energy available for flights, and do not run into any issues with range. In reality, AAM aircraft will have restrictive ranges, in some cases extremely restrictive. Therefore, congestion within the airspace poses a threat to aircraft and may force unplanned landings in order to recharge/refuel the aircraft. The primary goal of this dissertation is to explore air traffic flow and its concepts, and a separate consequence of air traffic flow such as range issues was not explored for simplicity. If the range issues were fully considered then the negative impacts of congestion would be even worse than what is shown in this work, since congestion would slow throughput and serve to effectively shorten the range of aircraft. Aircraft would spend more time on intermediate recharging stops, and AAM operators may conclude that some trips are not feasible due to congestion and range issues.

Aircraft are assumed to be able to detect and avoid other aircraft independently, in a decentralized manner, without communication between aircraft. While the current commercial aviation system relies heavily on a centralized air traffic control system to deconflict the airspace, it is acknowledged that a new system will be needed for AAM due to the density of operations (FAA 2020). The shape of the UTM system is still under development, however a piece of the system will be that aircraft can detect other aircraft and avoid them within airspace independently, at least as a fail-safe option should communications with a centralized UTM system fail. The assumption that aircraft deconflict individually and without communication may not reflect the actual system in the future, but it serves as a reasonable approximation for how aircraft may deconflict. A coordinated, centralized approach to deconfliction may improve the efficiency of conflict resolution which could mitigate some of the negative effects of conflicts and congestion, however the negative effects will remain and the broad concepts and patterns behind air traffic flow will still apply.

Aircraft Homogeneity

Aircraft are assumed to be the same in a number of ways in order to simplify the air traffic flow problem. Aircraft are assumed to have the same maximum speeds, spacing requirements, capabilities, missions, and priorities. Maximum aircraft speeds, spacing requirements, and capabilities reflect a system in which all aircraft are the same, which will not be true for AAM. Instead, aircraft will have differing capabilities and travel speeds, which will change the behavior of traffic and the interaction between aircraft. Heterogeneity between aircraft in capabilities can worsen the effects of traffic flow by producing more conflicts for aircraft with varied speeds, and by making some processes such as conflict detection and resolution more difficult.

Aircraft are assumed to all have the same mission type: a simple transit between origin and destination similar to an air taxi service. While air taxi may be a common use for AAM, it will not be the only use, and operations with different shapes may be present. For example, a package delivery operation could have the same origin and destination, and make numerous intermediate stops in the same area in between. This assumption is somewhat justified by the proposed separation of different use cases, for example package delivery operations may occur at a much lower altitude than air taxi operations. Furthermore, different operation shapes will not alter the fundamental formation of congestion within airspace.

There is an assumed homogeneity of priorities among aircraft. Consistent to the air taxi use case, aircraft always prioritize minimizing travel times. The initial route choice for aircraft assumes that aircraft fly the fastest possible route to their destination, and the conflict resolution algorithm identifies the fastest possible trajectory that is free of conflicts. However, actual aircraft priorities may be more nuanced. Flying at a faster speed could be more expensive or create discomfort, therefore providing some disincentive for finding the absolute minimum of travel times. Additionally, certain airspaces may be more sensitive to external costs such as noise, and therefore aircraft may choose alternative slower paths or different operations. Emergency aircraft will also share the airspace with AAM aircraft, and priority will be given to those aircraft in a congested airspace. By introducing other priorities for aircraft and operators to consider, there may be somewhat different behavior by aircraft in the system.

Altitude Layers

Within the simulation aircraft are initially assigned to an altitude layer. While aircraft may deviate from the layer during conflict resolution, aircraft generally stay within or near the altitude layer. This has the effect of simplifying the air traffic towards something more similar to a two-dimensional rather than a three-dimensional traffic flow. The layer-assignment assumption has been made in previous similar research (Hoekstra et al. 2018a, Neto et al. 2019) because it approximates how the air system currently operates. In the current air system aircraft are often assigned to an altitude level for the cruising portion of flight, only climbing or descending near take-off and landing or because of conflict resolution.

The air traffic flow models developed in chapter 4 and the experiments in chapter 5 and 6 are all shaped by this assumption. Within each the models and simulations assume a system in which aircraft largely interact with each other on the same or similar altitude levels, and do not approach from above or below. An alternative formulation might extend this work to account for varied angles of attack among aircraft and a system in which aircraft ascend and descend more freely. In this formulation a consideration for the conditions under which aircraft would change altitudes would be needed. However, the current airspace system and the proposed AAM concepts of operation do largely rely on assigned altitude layers with only minor deviations from aircraft, and therefore this work focuses on developing air traffic flow models for that regime of aircraft operations.

The notable exception to this assumption is near vertiports. Near take-off and landing changes in altitude are ubiquitous, and there will be different traffic rules to safely manage the movement of aircraft near vertiports. The author leaves the management of air traffic near vertiports and resulting congestion to other research, choosing instead to focus on the development of congestion within the cruising portion of aircraft flight.

Demand Assumptions

The demand for AAM services was in general uniformly distributed over a number of vertiports, and normally distributed across time to generate a peak period effect. During operations however, demand will not be uniformly distributed over a network, but may concentrate on a certain number of high-demand locations, such as airports or central business districts. This assumption was made for simplicity of the problem and to avoid the development of demand behavior models for a service that does not yet operate. However, the actual experience of AAM may find that concentrating demand in key areas will rapidly increase the density and congestion of the local airspaces, presenting greater challenges for the traffic flow on the network.

Weather and Wind

This dissertation does not model the effects of weather or wind on air traffic or aircraft movement, thereby making the assumption of perfectly still wind and perfect weather for aircraft. These conditions will generally not exist for actual AAM operations, and weather and wind conditions will affect AAM aircraft. Wind conditions, for example, may slow aircraft traveling in certain directions, or make planned future aircraft positions less certain. In order to simplify the air traffic flow problem and focus on the air traffic flow problem at the core of this dissertation, weather conditions are ignored.

Perfect and Instantaneous Information

All aircraft are assumed to know the positions and future trajectories of all other aircraft at all times. This system of perfect information may not exist in actual AAM operations, because it requires perfect communication between aircraft. Additionally, information is available to aircraft instantaneously, and aircraft make instantaneous decisions on processes such as conflict resolution. Both of these assumptions will be incorrect to some degree in a future AAM system. For a system with human-piloted aircraft the assumption of instantaneous decisions will be especially incorrect. It would be difficult to model the behavior and reaction of pilots within the system however, so the focus of the dissertation was kept on macroscopic traffic flow and an assumption of perfect and instantaneous information maintained. Relaxing this assumption could be achieved in future work. A relaxation would find that imperfect and non-instantaneous information would make conflict detection and resolution more difficult, limiting the options for resolving conflicts and making the negative impacts of conflicts larger on average. Therefore this assumption indicates that the results understate the severity of the negative impacts of conflicts on traffic flow and congestion.

3.2 Definition of variables

Before air traffic flow models can be developed, first the definitions of the key traffic flow measures must be discussed, which is done in this section. Equations for the measurement of these variables are included where appropriate. Five key measures are tracked closely using the trajectories of aircraft in the airspace: conflicts, density, actual speed, effective speed, and effective flow rate (or throughput).

A conflict is defined as the *predicted* intrusion of one aircraft into the spacing requirements of another aircraft. Conflicts do not imply any contact or unsafe interaction between aircraft, only that aircraft would experience a loss-of-separation if the conflict were not resolved by altering aircraft trajectories. Conflicts are detected in a pair-wise manner and each conflict counted affects two aircraft. If there are multiple predicted conflicts involving the same aircraft simultaneously, the conflicts are still counted based on the pairs of aircraft affecting each other. The spacing requirements in this paper take the shape of an ellipsoid, which has been proposed for the AAM context because it offers greater flexibility and better captures the vertical and horizontal capabilities of AAM flight (Geister and Korn 2018). The count of conflicts is commonly translated into a conflict rate in this dissertation. The conflict rate expresses the number of conflicts as a ratio with the length of the time window studied and the volume of airspace. Therefore conflict rate is useful for comparing the number of conflicts between non-uniform airspace sizes and shapes. Equation 3.1 shows the conflict rate ratio.

$$C = \frac{Number\ of\ conflicts}{Airspace\ volume * Time\ window} \qquad \text{(Eqn. 3.1)}$$

Density refers to the number of aircraft within a given section of airspace. In this work density is measured in terms of vehicles per cubic mile or vehicles per square mile. The density of aircraft used for studying air traffic flow within a given airspace is found using a multi-dimensional expansion of Edie's definitions (Edie 1965). Equation 3.2 shows the calculation of the vehicle density in an airspace of dimensions X and Y when measuring over a time window T. While this work averages aircraft density over a time window, alternatively an instantaneous density could be found by dividing the aircraft count by the product of the airspace dimensions. Other work has proposed alternative methods of measuring density, such as average time separation between aircraft or occupancy of the airspace (Golding 2018). However, this measure was chosen for its ease of interpretability and application to airspace.

$$k = \frac{\sum_n t_i}{T(XY)} \qquad \text{where } t_i \text{ is the time vehicle n spends in the airspace} \qquad \text{(Eqn. 3.2)}$$

The speeds and flow rates of aircraft are broken into two types: actual and effective. The actual speed refers to the magnitude of Euclidean distance a vehicle is traveling in a given time in any direction. Actual speed values are important in the operation of vehicles and are used in the conflict prediction models. Meanwhile the effective speed measures the magnitude of distance moved towards the vehicle's destination in a given time. Effective speeds are useful for predicting travel times or demonstrating the cost of deviations from a direct trajectory. Both actual and effective speeds are measured by considering the sum of all distances (actual or effective) moved in the airspace divided by the amount of time considered. Their calculations are shown in equations 3.3 and 3.4. d_i refers to the actual distance vehicle i travelled in the study volume and time window. e_i represents the effective distance vehicle i travelled in the study volume and time window. Each speed is the sum of the distances travelled by each vehicle divided by the sum of the amounts of time spent in the volume during the time window.

$$v = \frac{\sum_i d_i}{\sum_i t_i} \qquad \text{(Eqn. 3.3)}$$

$$e = \frac{\sum_i e_i}{\sum_i t_i} \qquad \text{(Eqn. 3.4)}$$

In a similar way there are two flow rates: actual flow rate and effective flow rate. The actual flow rate refers to the flow of aircraft through airspace in any direction and is not particularly interpretable. This work focuses instead on the effective flow rate, which is the flow of aircraft towards each aircraft's goal. The effective flow rate refers to the number of vehicles that can move through airspace in a given time towards each vehicle's destination. This is an important operational output measure as it defines the throughput of airspace. The flow rates were also calculated using an expansion of Edie's definitions (Edie 1965) as shown in equation 3.5. Equation 3.5 measures the sum of all distances moved within an airspace of dimensions X and Y over the time window considered T.

$Q_e = \frac{\sum_n e_i}{YXT}$ where e_i is the effective distance within the airspace moved by vehicle i (Eqn. 3.5)

3.3 Microscopic Traffic Simulator Overview

The simulator develops and tracks the movement of hypothetical advanced air mobility vehicles in a three-dimensional airspace. These vehicles are modeled as agents and points moving from an origin station to a destination station, both of which are located on the ground (zero altitude). Each flight has a unique combination of an origin station, destination station, and starting time. Simulator setups can vary according to the experiment being run, for example an unstructured airspace scenario would incorporate no airspace restrictions and randomized headings. A corridor scenario would include restricted airspaces to the sides of the corridor, and would incorporate similar aircraft headings while vehicles move through the corridor. The specifics of each simulated scenario are included with the results of that scenario, however general descriptions are given here.

The origin and destination stations are randomly assigned from a set of vertiports, generally based on either a uniform or normal distribution. For most scenarios this creates somewhat randomized headings of aircraft through the airspace. The starting time for each vehicle is randomly assigned based on a normal distribution, with the mean of the distribution set to the middle of the simulation. This emulates a peak hour scenario in which traffic increases to a peak point and then decreases.

Each flight has three phases, ascending, transiting, and descending. The transiting and ascending goals are both at a randomly-assigned altitude, within specific increments, effectively creating multiple levels of traffic as used in (Neto et al. 2019, Bulusu 2019, Metropolis 2015). Depending on the scenario a vehicle may have multiple transiting goals, which act similar to waypoints in that they represent key navigational points for each aircraft to pass through. Maximum velocities are given to each aircraft for each direction, although no minimum velocities are specified. This assumes that each vehicle has the ability to stop and maintain position while airborne, or “stand and hover”. This ability is common in AAM vehicle configurations under development (Bacchini and Cestino 2019) and is similar to helicopters.

3.4 Key Simulator Constructs

Each vehicle, i, in the simulation has a trajectory, $x_{i,t}$, which tracks all past and future three-dimensional position vectors according to a discretized time variable, t. Figure 3.1 depicts vehicle trajectories in four-dimensions.

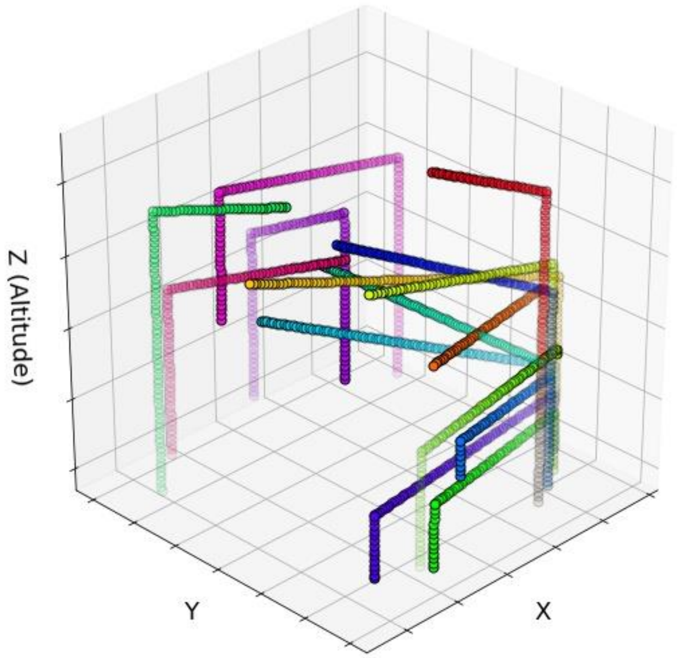


Figure 3.1. Depiction of vehicle trajectories within the simulator.

The current position of each vehicle, i, is tracked with y_i. The vehicles do not initially plan their entire routes, they only plan for a certain number of time periods in advance, which is the “look ahead” window. During each time period, T, each vehicle moves from its current position, y_i, to its next planned position, $x_{i,T+1}$, and plans a new position, $x_{i,T+LookAhead+1}$ based on the shortest path from $x_{i,T+LookAhead}$ to the current goal. Past values of $x_{i,t}$ can never be changed, as these are the record of previous vehicle positions. The conflict detection and resolution algorithms only check future positions, so they can only see conflicts within the look ahead window. Vehicle acceleration is not explicitly considered in the vehicle trajectory. Acceleration was excluded in order to simplify simulation of vehicle trajectories. While this is a limitation, in the author's opinion the patterns of air traffic flow which are this work's primary focus will not be significantly impacted.

3.5 Conflict Detection

There is a minimum spacing requirement between vehicles, which is specified according to the scenario tested. If the future trajectories of two vehicles will violate the minimum spacing requirement, they are identified as a conflict. The conflict detection is shown in equation 3.6 and works as follows. During each time period, t, each vehicle, i, constructs a list of nearby vehicles that are within a specified time distance. For each nearby vehicle, j, and each time period, t, in the look ahead window, the algorithm checks if the distance between $x_{i,t}$ and $x_{j,t}$ is below the minimum spacing requirement, as shown below. If yes, a conflict is recorded between the two aircraft.

$$\left|x_{i,t} - x_{j,t}\right| \leq spacing_{i,j} \quad \forall\, t \in Look\ Ahead, \forall j \in Nearby\ Veh \qquad \text{(Eqn. 3.6)}$$

Once all conflicts are identified, conflicts are resolved starting with the vehicle with the most conflicts. The conflict resolution algorithm is discussed in greater detail below.

3.6 Conflict Resolution

This simulation framework uses a non-linear program (NLP) for conflict resolution, as it offers more flexibility in solutions than other, rule-based algorithms. For more details on different types of conflict resolution, see section 2.5. An NLP allows the algorithm to evaluate many possible dimensional shifts and combinations to resolve conflicts including horizontal shifts, altitude adjustments, and speed adjustments. However, with large numbers of vehicles and conflicts such a scheme can become computationally expensive. Therefore, a simple NLP has been used with limited variables and constraints in an effort to keep solution times low. That NLP is presented below. The NLP presented here is also decentralized, meaning that it is resolved by individual aircraft without coordinating with other aircraft. Decentralized conflict resolution is an important capability for AAM vehicles which may not be able to rely on excellent communication and coordination, although better coordination between vehicles would be expected to generate more optimal solutions.

The NLP works by evaluating the values of $x_{i,t}$, the position vector of a single vehicle, i, at time, t, for the t values within the look ahead window. The objective (equation 3.7) is to minimize the remaining travel time at the end of the look ahead window between the future position vector of the aircraft, i, and the goal of the aircraft, $goal_i$. This objective is used as a proxy for the true objective of completing the journey as quickly as possible.

Indices:

t = current time period

i = current vehicle that the model is rerouting

j = any nearby vehicle that is not the current vehicle

Variables:

$x_{i,t}$ = position vector of vehicle, i, at time, t

Fixed Parameters:

$goal_i$ = destination position vector of current flight leg of vehicle, i

speed_i = maximum speed of vehicle, i

$\text{spacing}_{i,j}$ = minimum spacing required between vehicle i, and nearby vehicle, j

$$\min\left|x_{i,t+look\ ahead} - goal_i\right| \qquad \text{(Eqn. 3.7)}$$

$$s.t.\left|x_{i,t+1} - x_{i,t}\right| \leq speed_i \quad \forall\, t \in look\ ahead \qquad \text{(Eqn. 3.8)}$$

$$\left|x_{i,t} - x_{j,t}\right| \geq spacing_{i,j} \quad \forall\, t \in look\ ahead, \forall j \neq i \qquad \text{(Eqn. 3.9)}$$

There are two groups of constraints for the NLP, that the aircraft cannot exceed a maximum speed (equation 3.8), and that the aircraft cannot violate the spacing requirements of other aircraft (equation 3.9). The speed constraint is represented as the ellipsoidal distance between the current position, $x_{i,t}$, and next position, $x_{i,t+1}$, must be below the prescribed maximum speed value. This constraint must hold for all time steps, t, in the look ahead window. The spacing constraint requires that the ellipsoidal distance between the current vehicle, i, and any nearby vehicle, j, must be greater than the prescribed spacing requirements. This constraint must hold for all nearby vehicles, j, and for all time periods, t, in the look ahead window.

Once a result is reached, the NLP will update future position vectors, x_{it}, for the currently evaluated aircraft, i. The updated positions will represent the fastest possible path through the imminent conflict while avoiding the trajectories of nearby vehicles. If the vehicle cannot move closer to its goal with the constraints given, a conflict resolution is not found and the algorithm changes the vehicles future positions, $x_{i,t}$, to the last position without a conflict. This heuristic effectively tells the vehicle to “stand and hover” and is necessary to avoid conflicts and reduce observed gridlock in the simulation. After each conflict resolution is complete, the simulation updates the list of future conflicts.

3.7 General Simulation Assumptions

Input parameters into the simulation include the origin and destination stations, the horizontal and vertical speed of the vehicles, the horizontal and vertical spacing requirements around each vehicle, and the number of time periods to simulate. While each scenario studied uses different inputs, in general the following assumptions are used unless otherwise specified. The horizontal speed of 100 mph represents a common cruise speed of UAM vehicles currently in development (Bacchini and Cestino 2019), although faster vehicles have been proposed (the effect of vehicle speed on air traffic flow is studied as well). The vertical speed of 5 mph was chosen based on expected climbing rates (Patterson et al. 2018). It is important to note that the vehicles in this simulation may “stand and hover” and climb vertically, similar to a helicopter. This ability is not common to all types of AAM vehicles, as some fixed wing designs depend of forward motion to generate lift.

The horizontal spacing requirements are derived as 20 seconds times the speed, effectively dictating that no vehicle can be within 20 seconds of another vehicle. A vertical spacing requirement of one-tenth of a mile is used. Vehicles do not consider all trajectories during conflict detection and resolution, only those within a nearby distance. This allows for computational simplicity. The nearby distance is tied to the spacing values, and must be larger than the spacing values so that vehicles recognize conflicts before one occurs, although the 2x ratio is arbitrary. The time steps of the model are 10-second steps, with a 90-second look ahead, indicating that vehicles are effectively planning for as far as 90 seconds into the future.

Table 3.1. Simulation input parameters and assumptions

Vehicle Parameter	Value	Assignment
Origin Point	3D position vector	Randomly distributed station
Destination Point	3D position vector	Randomly distributed station
Starting Time	Time period	Normally distributed random time
Horizontal Speed	100 mph	Uniform
Vertical Speed	5 mph	Uniform
Horizontal Spacing	0.555 miles	Uniform
Vertical Spacing	0.104 miles	Uniform
Nearby Distance	2x spacing req’ts	Uniform
Simulation Parameters	Value	
Look Ahead Window	90 seconds	
Time Step	10 seconds	
Length of Simulation	5,000 seconds (1h 20m)	

Chapter 4

In this chapter the air traffic flow models are developed. Conflict probability models for aircraft (see section 2.6) are used as a starting point in section 4.2, and are developed to provide relationships between aircraft density, conflict rates, actual speed, effective speed, and effective flow rate. In sections 4.3, 4.4 and 4.5 these macroscopic air traffic flow models explain the patterns of behavior expected in air traffic flow according to aircraft density, which is used as an independent variable. Using the models the impacts of various operational parameters are explored in sections 4.6 through 4.8, including vehicle spacing, maximum vehicle speeds, and allowable heading ranges between aircraft, which is used in geo-vectored or restricted traffic flow. The traffic flow model relationships are validated using simulation of air traffic in sections 4.9 through 4.11. The relationship between the air traffic flow models and vehicle travel times and airspace capacity are explored in section 4.12, demonstrating some of the operational uses of these models. Finally the findings, insights, and broader impacts are discussed at the end of the chapter in section 4.13.

4.1 Three Key Concepts

The air traffic flow models derived and tested in this work encompass three key concepts for the development of airspace congestion. Firstly, aircraft density in airspace creates conflicts, because more vehicles in the same airspace increases the chances of conflicts for each vehicle. This relationship has been established by a wide body of work in aircraft conflict prediction models, which this study draws from (Mitici and Blom 2019, Sunil et al. 2018b]. Secondly, conflicts reduce effective and actual speeds of aircraft. It is assumed that without conflicts vehicles would travel on the shortest path to their destination to minimize travel time. Therefore, to resolve a conflict one or both vehicles must deviate from the fastest route along one or more dimensions. This deviation will always decrease effective speed because the aircraft is no longer traveling towards its destination as fast as it could be. Some conflict resolutions will also reduce actual speed. Therefore, aggregated over many conflicts the average actual speed will decrease along with, but at a slower rate than, effective speed. Thirdly, the effective flow rate, or throughput, is impacted by changes to the aircraft density and effective speeds. This is consistent with the fundamental identity of traffic flow, which holds that the flow rate is the product of the density and speed.

These three concepts, summarized in figure 4.1, form the order in which rising aircraft densities in airspace affect traffic flow, and also the order in which the theoretical models are developed in this chapter. The next section will discuss the gas law model for predicting numbers of conflicts and how it has been adjusted in this work. After that the relationships between aircraft actual and effective speeds and density are derived, followed by the models of actual and effective flow rates dependent on density.

Figure 4.1. The process by which aircraft density in a given airspace affects the traffic flow of aircraft.

4.2 Gas Law Conflict Prediction Model

There is a rich literature of aircraft conflict prediction models (Mitici and Blom 2019). These models include gas law models, Monte Carlo simulations, and Markov chain approximation. The gas law model, named that way because it is inspired by the study of gas molecule collisions in chemistry, is useful for predicting conflict probabilities and rates between aircraft (Sunil et al. 2018b). The model has been adjusted and rewritten in a variety of ways depending on the context and needs of the work. The same applies here, where the model is written in a form that highlights the role of vehicle parameters and vehicle density in the number of conflicts, which is a primary objective of this work. The conflict prediction model is initially applied to an unstructured airspace that assumes random headings for aircraft. The model is then adjusted for restricted headings in section 4.5. The gas law model is applicable to multi-dimensional situations, but the models developed here are simplified for the two-dimensional case. This simplification primarily affects the relative velocity adjustment term.

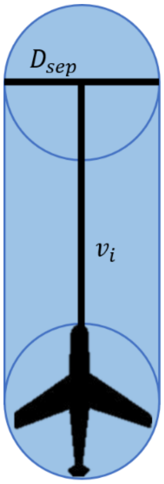


Figure 4.2. Depiction of the airspace each aircraft searches for conflicts.

The gas law model begins by trying to estimate the conflict rate for a single aircraft in airspace. To do so, the expected number of conflicts in the volume or area of airspace immediately ahead of the aircraft is calculated. Figure 4.2 demonstrates the shape of the volume of the airspace considered. The calculation of the expected conflict rate for a single aircraft is shown in equation 4.1. First the size of the volume or area is found by multiplying the cross-sectional area of the airspace the aircraft occupies (defined by the separation requirements) and the relative speed of the aircraft compared to other aircraft. This model considers unstructured airspace with aircraft having uniformly random headings relative to each other, and therefore the relative speed of the aircraft is $\sqrt{2} * v_i$ where v_i is the actual speed of the aircraft. The volume of airspace searched can then be multiplied by the average density of aircraft in airspace to estimate the number of aircraft in the volume, which will correspond to the number of conflicts. In equation 4.1, C_i is the expected conflict rate for aircraft, i, k is the density of aircraft, v_i is the current actual speed of aircraft, i, and D_{sep} is the cross-sectional area of the separation requirements.

$$C_i = \sqrt{2} * v_i * D_{sep} * k \qquad \text{(Eqn. 4.1)}$$

Once the conflict rate for each aircraft is determined it is multiplied by T, the time length of the window which each aircraft is searching for conflicts. The product is the number of expected conflicts for each aircraft. This number is then multiplied by the number of aircraft considered, which can be rewritten as $k * Vol$, or the density of aircraft multiplied by the total volume of airspace studied. Lastly the number of conflicts is divided by 2 so that conflicts are not double-counted. Applying these factors creates an equation for the expected number of conflicts between all aircraft in the considered airspace, which is shown in equation 4.2. In this equation C is the expected total number of conflicts in the airspace, v is the average actual speed of the aircraft considered, D_{sep} cross-sectional area of the separation requirements, T is the time length of the window considered for conflicts, and Vol is the total volume of the airspace studied.

$$C = \frac{\sqrt{2}}{2} * v * D_{sep} * k^2 * T * Vol \qquad \text{(Eqn. 4.2)}$$

The conflict prediction model yields several observations from the relationships between variables. First, the number of conflicts increases linearly with two vehicle parameters: the cross-sectional area of the separation requirements and the aircraft speed. These relationships will be explored in further detail in sections 4.6 through 4.8. Second, the number of conflicts increases due to density according to a power law. This insight reflects the first key concept: that aircraft density creates conflicts. It is this power relationship that is critical to understanding the aircraft traffic flow, because the number of conflicts will not just increase at higher densities, but increase rapidly. From here traffic flow models utilizing the conflict prediction equation will be derived to demonstrate the role of vehicle parameters in the development of traffic flow.

4.3 Theoretical Speed-Density Models

In the previous section a conflict prediction model dependent on vehicle parameters and vehicle density was developed using the gas law methodology. In this section traffic flow models are derived that utilize the conflict prediction model in order to understand how vehicle parameters affect the traffic flow.

After the first key concept in which aircraft density leads to conflicts is the second concept, that resolving these conflicts reduces both the actual and effective speeds of aircraft. We will begin by deriving the actual speed- density relationship, because this will be necessary for the other traffic flow models. Assuming that aircraft fly the most direct route at the maximum possible speed unless they are impacted by a conflict it is possible to model the average actual aircraft speed as shown in equation 4.3. In this equation the average actual aircraft speed, v, is the maximum actual aircraft speed, v_{max}, less the average speed loss per vehicle, where the speed loss is the average actual speed loss per conflict, b, multiplied by the number of conflicts, C, divided by the number of aircraft, n.

$$v = v_{max} - \frac{b * C}{n}, \text{ where n is the number of aircraft} \qquad \text{(Eqn. 4.3)}$$

In equation 4.3, C is the total number of conflicts among all aircraft in the studied airspace, and the conflict prediction model developed above describes this. However, the conflict prediction model depended in part on the actual aircraft speed, which is what is solved for here, so the relationship between actual speed and density will not be linear, as we will see momentarily. By substituting equation 4.2 into equation 4.3, we arrive at equation 4.4.

$$v = v_{max} - \frac{b * \frac{\sqrt{2}}{2} * v * D_{sep} * k^2 * T * Vol}{n} \qquad \text{(Eqn. 4.4)}$$

It is possible to rewrite n, the total number of aircraft in the airspace studied, as the product of $k * Vol$, the density of vehicles and the volume of airspace. Making this substitution and performing some algebra arrives at an actual speed- density function as shown in equation 4.5. D_{sep} represents the cross-sectional area of the spacing requirements, k is the average vehicle density, and T is the time window over which the average speed is measured.

$$v = \frac{v_{max}}{(1 + \sqrt{2} * b * D_{sep} * k * T)} \qquad \text{(Eqn. 4.5)}$$

It is immediately notable that this speed-density model is not linear as in Greenshields model for highway traffic (Greenshields et al. 1935). Again, this is because the average actual speed is modeled as a function of the number of conflicts in airspace, and the number of conflicts itself is dependent on the actual speed of aircraft. The full implications of this relationship will be explored in section 4.6, but for now it is notable that the average actual vehicle speeds have an inverse relationship with both vehicle density and the spacing requirements, as opposed to a negative linear relationship.

The derivation for the average effective vehicle speed as a function of density begins in a similar way. The average effective speed, e, is considered to be the maximum effective speed,

e_{max}, minus the effective speed loss, which is found by multiplying the effective speed loss per conflict, a, by the total number of conflicts, C, and dividing by the total number of vehicles, C. It should be noted that the rate of effective speed loss per conflict, a, is different than the rate of actual speed loss per conflict, b, depending on the form of conflict resolution used. These terms are further explained in equation 4.10 below. The average effective speed as a function of conflicts is set up in equation 4.6.

$$e = e_{max} - \frac{a * C}{n} \qquad \text{(Eqn. 4.6)}$$

Again, we can substitute in equation 4 for the total number of conflicts, creating equation 4.7 as follows.

$$e = e_{max} - \frac{a * \frac{\sqrt{2}}{2} * v * D_{sep} * k^2 * T * Vol}{n} \qquad \text{(Eqn. 4.7)}$$

However, unlike with the average actual speed, the average effective speed does not directly influence the number of conflicts, which will keep the relationship between average effective speed and average actual speed and density linear. This can be seen once we again substitute in $k * Vol$ for n and simplify the equation with algebra to arrive at the effective speed- density model shown in equation 4.8.

$$e = e_{max} - \sqrt{2} * a * D_{sep} * v * k * T \qquad \text{(Eqn. 4.8)}$$

From this model it appears that there is a linear relationship between effective speed and density, however the actual speed, v, is included in the model and depends on density as well. So in effect the effective speed-density relationship follows a shape similar to the actual speed-density model. The actual speed term, v, is variable according to equation 4.5, and can be removed from the model by substitution, with the result being an effective speed – density function dependent only on the density variable. This is shown in equation 4.9.

$$e\ (k) = e_{max}\ -\ \sqrt{2}\ * a\ * D_{sep}\ * \frac{v_{max}}{(1 + \sqrt{2} * b * D_{sep} * k * T)}\ * k\ * T \qquad \text{(Eqn. 4.9)}$$

Both actual and effective speed models are dependent on the average speed loss per conflict, term b in equation 4.3 and term a in equation 4.6. These terms are important because they relate the number of conflicts to speed reductions which result from conflict resolutions. Logically we can conclude that a, the effective speed loss per conflict, will always be larger than or equal to b, the actual speed loss per conflict, because effective speed measures the amount of the actual speed that is oriented towards the goal. The average speed losses per conflict are difficult to estimate in part because they can fluctuate greatly due to the specifics of the context: including the conflict resolution algorithm used, c, the relative headings of the two aircraft, h, the separation volume or area of the aircraft, V_{sep}, the density of other nearby aircraft, k, and the speeds of the aircraft, v. The impact of these relationships on average speed loss and the relationship between actual speed loss per conflict, b, and effective speed loss per conflict, a, are expressed in equation 4.10.

$$a\ (c, h, V_{sep}, k, v) \geq b\ (c, h, V_{sep}, k, v) \qquad \text{(Eqn. 4.10)}$$

Given that the average speed loss per conflict terms are difficult to predict and model, the values for these terms were instead obtained from calibration. By simulating aircraft interactions at low and medium densities, it was possible to calibrate estimates of the terms' values that could be used to model the traffic flow of interest in high density scenarios. This approach to calibrating key model parameters at low density has been used in previous work on conflict prediction and early approaches to air traffic flow models (Jardin 2004, Sunil et al. 2018a, Tereschenko et al. 2020). Based on the calibration performed in this work, several relationships between key parameters and average speed loss per conflict were observed, which largely follow logical deduction. For example, aircraft with larger separation requirements will require longer detours in trajectories, creating a positive relationship between the volume or area of the separation requirements and the speed loss per conflict. Aircraft flying in higher-densities will on average see a higher speed loss because the other nearby aircraft decrease the solution space for conflict resolution. Additionally, there will be a positive linear relationship between the speed of the aircraft and the speed loss per conflict because faster moving aircraft will have a higher relative speed and the relative speed will need to decrease more to avoid an in-crossing conflict immediately ahead of the aircraft.

4.4 Theoretical Flow Rate – Density Model

The effective flow rate of aircraft through airspace is also of interest as a measure of the productivity of the airspace. The fundamental identity holds that flow rate is the product of speed and density, and this applies here to effective speed as well in equation 4.11, where Q_e represents the effective flow rate of aircraft, k is the density of aircraft, and e is the average effective speed:

$$Q_e = k * e \qquad \text{(Eqn. 4.11)}$$

Expanding equation 4.11 by substituting in the effective speed-density model for e reveals a parabolic model in equation 4.12. This parabolic model will reflect the shape of the fundamental diagram. In this pattern the effective flow rate will initially increase proportionally with the density, but as density increases more conflicts occur and vehicle speeds decrease, which results in decreasing returns to density before ultimately a critical density is reached and the flow rate actually begins to decline.

$$Q_e = k * e_{max} - \sqrt{2} * a * D_{sep} * v * k^2 * T \qquad \text{(Eqn. 4.12)}$$

The model of effective flow rate can be reduced to a function of only the density variable, k, by substituting in equation 4.5, the actual speed-density model. The resulting function is equation 4.13.

$$Q_e(k) = k * e_{max} - \sqrt{2} * a * D_{sep} * \frac{v_{max}}{(1 + \sqrt{2} * b * D_{sep} * k * T)} * k^2 * T \qquad \text{(Eqn. 4.13)}$$

These past two sections have described the derivation of traffic flow models utilizing the conflict prediction model. The next section will explore the vehicle parameters in these models and show how traffic flow patterns of aircraft change under different parameter contexts. The implications of these relationships for AAM planners and operators are discussed.

4.5 Adjusting for Heading Restrictions

As mentioned above, the gas law model generally assumes that aircraft are approaching each other with random headings between aircraft. This assumption will not apply to geo-vectored or fixed-route airspace, both of which restrict the headings of aircraft. Geo-vectored airspace restricts aircraft headings by a zone or altitude level. Fixed-route is defined here as aircraft traveling in a single direction along a pre-determined route without any intersections with other routes. To evaluate traffic flow for geo-vectored airspace a new conflict prediction model is needed that does account for restricted headings between aircraft. To begin with Equation 4 will be further developed to create a conflict prediction model for geo-vectored airspace, taking advantage of some similarities between geo-vectored and unstructured airspace.

Within Equation 4 is a term for the relative speed of aircraft, $\sqrt{2} * v$ (the 1/2 term only serves to avoid double-counting conflicts, since conflicts occur in pairs). The relative speed refers to the average relative speed of another aircraft, j, when compared to the current aircraft, i. The $\sqrt{2}$ in this term serves as a constant that adjusts the average actual speed of aircraft j to the relative speed of aircraft j. However, $\sqrt{2}$ is a value based upon the assumption of random headings between aircraft. Geo-vectored airspace must identify the expected relative velocity of aircraft for a range of allowable aircraft headings. When the range of headings is small so will be the relative velocity of aircraft, and vice versa.

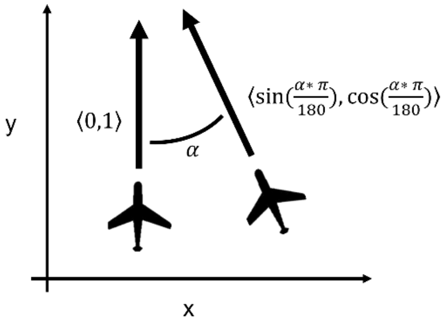


Figure 4.3. Velocity comparison of two conflicting aircraft.

When considering two aircraft approaching each other in geo-vectored airspace (see figure 4.1), if aircraft i is assumed to have a velocity vector of $\langle 0,1 \rangle$, and aircraft j has a heading that is α degrees different from aircraft i and also of magnitude 1, then the relative velocity vector between aircraft i and aircraft j is $\langle 0 - \sin(\frac{\alpha * \pi}{180}), 1 - \cos(\frac{\alpha * \pi}{180}) \rangle$. The magnitude of that velocity vector represents the relative unit speed of aircraft j compared to aircraft i. Multiplying that velocity vector by the average speed, v, creates Equation 4.14, which predicts v_r, the relative speed between two aircraft.

$$v_r \;=\; v * \sqrt{\left(0 - \sin\left(\frac{\alpha * \pi}{180}\right)\right)^2 + \left(1 - \cos\left(\frac{\alpha * \pi}{180}\right)\right)^2} \quad \text{(Eqn. 4.14)}$$

Using a Pythagorean identity this equation can be further simplified to Equation 4.15 below.

$$v_r \;=\; v * \sqrt{\left(2 - 2\cos\left(\frac{\alpha * \pi}{180}\right)\right)} \qquad \text{(Eqn. 4.15)}$$

With the relative speed of two aircraft with a heading difference of α determined. Next, we can replace the term α, the heading difference, with an expression of the expected difference in headings. The expected difference of values from a uniform distribution is $\frac{2}{3} * range$, therefore the expected difference in headings is $\frac{2}{3} * heading\_range$. This expected difference in headings will be used throughout the remainder of this work, but it should be noted that for non-uniform distributions of headings the expected difference in headings must be accounted for in this term.

$$C = \frac{\sqrt{\left(2 - 2\cos\left(\frac{\alpha * \pi}{180}\right)\right)}}{2} * v * \; A_{XS} * \; k^2 * Vol * T \qquad \text{(Eqn. 4.16)}$$

Inserting equation 4.15 into the conflict-density model creates Equation 4.16. In this equation it is shown that the number of conflicts in airspace, C, is determined in part by the difference in headings between aircraft, α, with larger heading differences creating more conflicts.

By adapting equation 4.5 with the updated relative velocity term, we arrive at a speed-density relationship that incorporates heading restrictions, which is shown in equation 4.17. As before, this speed-density relationship is not linear due to the intertwined effects of vehicle speed and conflicts on each other. As vehicle speeds decline so do the number of conflicts, which slows the reduction in speed.

$$v = \frac{v_{max}}{(1 + \sqrt{\left(2 - 2\cos\left(\frac{\alpha * \pi}{180}\right)\right)} * b * A_{XS} * k * T)} \quad \text{(Eqn. 4.17)}$$

Equation 4.17 describes how a key consideration for airspace structures is the similarity of headings between aircraft, represented by α. Airspace with less structure to separate aircraft with dissimilar headings will have a high value of α, which in turn will create more conflicts and lower actual vehicle speeds. Similar adaptations to account for restricted headings can be made to equations 4.8 and 4.12, which create new effective speed-density and effective flow rate-density relationships, respectively. Equation 4.18 describes the effective speeds in relation to density, demonstrating that larger allowable heading ranges (α) will decrease effective speeds due to conflicts more quickly.

$$e = e_{max} - \sqrt{\left(2 - 2\cos\left(\frac{\alpha * \pi}{180}\right)\right)} * a * D_{sep} * v * k * T \quad \text{(Eqn. 4.18)}$$

Equation 4.19 shows the updated effective flow rate-density relationship, and similarly that larger heading ranges will experience a faster decline in the returns of density to flow rate.

$$Q_e = k * e_{max} - \sqrt{\left(2 - 2\cos\left(\frac{\alpha * \pi}{180}\right)\right)} * a * D_{sep} * v * k^2 * T \quad \text{(Eqn. 4.19)}$$

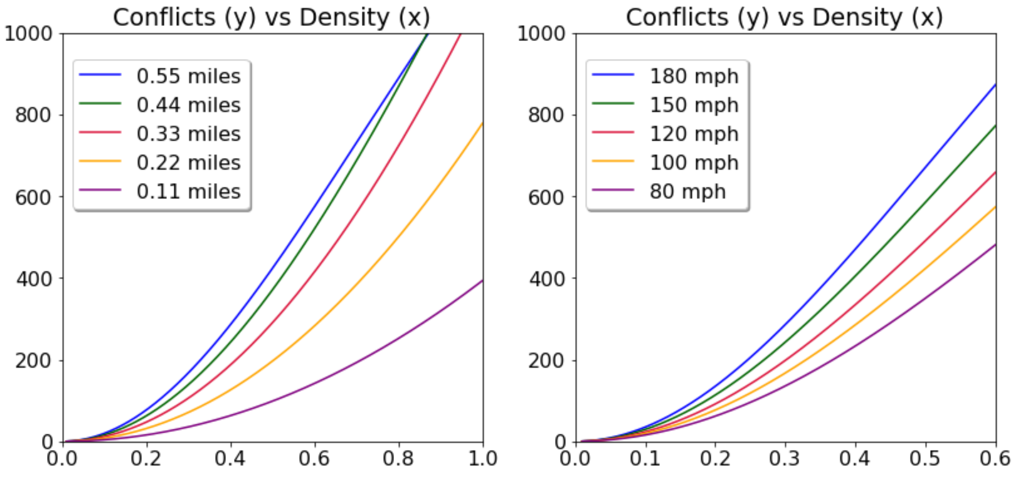
The impacts of allowable heading restrictions on traffic flow will be explored more in sections 4.6 through 4.8. However, it is apparent that in relation to unstructured airspace (in which the allowable heading range is large), restricted heading ranges offer the ability to reduce conflicts, and in turn offer higher aircraft speeds and throughput given the same density of aircraft within airspace. Of course, a trade-off for these benefits is the loss of navigational freedom for aircraft within these heading restrictions.

4.6 Patterns from Traffic Flow Models - Conflicts

In the previous section the theoretical traffic flow models were derived. These models covered the relationships between number of conflicts and density, average actual vehicle speed and density, average effective speed and density, and effective flow rate and density. In each of these models terms are included representing the separation requirements between aircraft (D_{sep}) and the speed of the aircraft (v), which are both important vehicle parameters that impact the patterns of traffic flow. In this section the patterns of traffic flow as a function of density are explored graphically using the theoretical relationships and insights are discussed. In addition, the effects of varying spacing and speed parameters are studied.

This section is primarily concerned with the shape of the patterns arising from the theoretical relationships, rather than the numerical outputs of the patterns. Therefore, throughout this section assumed values are used for the theoretical models to illustrate the patterns. The values on scales for each graph should not be considered closely except in relation to other values, as the assumed values may or may not reflect realistic conditions depending on the context.

The first key concept introduced in the theoretical models was that vehicle density in airspace creates conflicts, as a higher number of vehicles in the airspace raises the probability of conflicts for each vehicle. Equation 4.2 developed a conflict prediction model, which for a given density of aircraft and set of vehicle parameters could predict the number of conflicts in airspace. Figures 4.4 and 4.5 use that model to predict the number of conflicts in airspace for varying levels of density. Furthermore, in figure 4.4 the horizontal spacing requirements between vehicles is adjusted, while in figure 4.5 the maximum vehicle speed is adjusted.



Figures 4.4 and 4.5. Theoretical conflict-density relationships for varying spacing requirements (figure 4.4, left) and maximum vehicle speeds (figure 4.5, right).

The conflict patterns in these figures demonstrate a number of insights. The first is that higher densities have higher rates of conflicts in airspace, which is consistent with the first key concept that density creates conflicts. The relationship is not linear, but a power relationship instead, reflecting that the expected marginal number of conflicts added per vehicle is higher at higher densities. This is true because adding one vehicle to airspace does not just introduce the potential for that vehicle to have conflicts, but also increases the potential for conflicts with all other vehicles already in the airspace. This finding is significant because it suggests that at some point even small additions to density could create many more conflicts in airspace. Since each conflict requires some amount of travel time for a detour to resolve, at some point the marginal cost of adding vehicles to the airspace will exceed the marginal benefit of flying more aircraft simultaneously.

Varying the vehicle parameters of spacing and speed also create interesting patterns of conflicts. To begin with, higher spacing requirements are shown to be associated with higher conflict rates for a specific density across all levels of density. This occurs because larger spacing requirements between aircraft effectively means that each aircraft takes up more airspace, and therefore there is a larger chance that an aircraft trajectory intersects with other trajectories. Previous studies (Jardin 2004, Sunil et al. 2018b, Tereschenko et al. 2020, Bulusu 2019) have noted in various ways both theoretical and simulated this relationship between larger minimum spacing requirements and conflicts. While spacing requirements will ultimately be determined by safety considerations, these results indicate that even small improvements in operations that allow for the spacing needs to be lowered can significantly decrease the number conflicts in airspace that require resolution.

Equation 4.2 also demonstrated the role of vehicle speed in creating conflicts in airspace. Higher vehicle speeds lead to a higher conflict rate between vehicles at the same density because each vehicle is traveling farther and searching more airspace in its look ahead to identify conflicts and in that airspace will find more vehicles in conflict. This relationship between higher speeds and higher conflict rates is reflected in the differences between series in figure 4.5, in which faster vehicles are expected to develop more conflicts at a given density than slower vehicles. Based on this insight operators may consider operating aircraft at lower speeds, especially in higher density sections of airspace, in order to avoid higher conflict rates and the need for more complicated conflict resolutions.

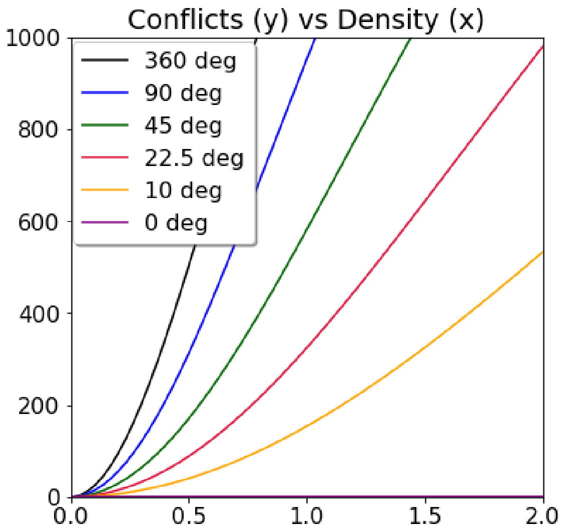


Figure 4.6. Theoretical patterns of conflicts versus aircraft density in geovectored airspace, with each series representing a different allowable heading range.

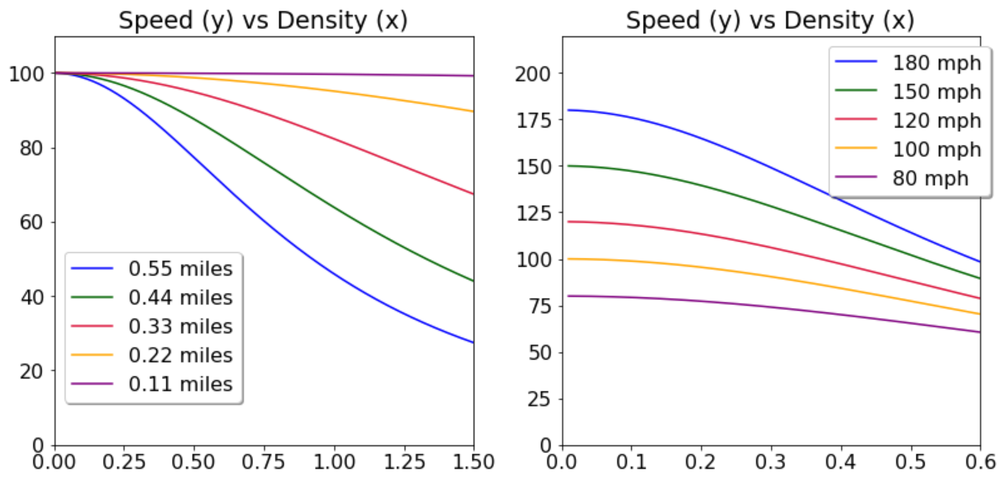
Figure 4.6 displays graphically the conflict-density relationships from equation 4.2 for a number of different heading ranges (represented by different-colored series). The number of conflicts for larger heading ranges is greater at all densities than smaller heading ranges. This is because larger differences in aircraft headings create more situations of aircraft crossing in front of other aircraft. The number of conflicts in airspace will also grow more quickly for higher heading ranges. These theoretical results suggest that airspaces with higher heading ranges and higher densities of aircraft could see very large numbers of conflicts. AAM operators and planners may wish to avoid the generation of these conflicts by using airspace structures to limit the heading ranges between aircraft or the density of aircraft within an airspace.

On the two extremes are heading ranges of 0 degrees, which represents all aircraft with the same heading as would be found in fixed-route airspace, and 360 degrees, which represents unstructured airspace with unrestricted headings. In fixed-route airspace, when considering uniform aircraft speeds, there should be no conflicts arising in the airspace because the aircraft cannot cross in front of each other, and the uniform speeds prevent aircraft from catching up to aircraft ahead. For unstructured airspace there will be many more conflicts, as the relative velocities of aircraft are high and the probabilities of aircraft crossing in front of each other are therefore higher.

4.7 Patterns from Traffic Flow Models - Speeds

Figures 4.7 and 4.8 were developed to explore the theoretical relationships between average actual vehicle speed and density as developed in equation 4.5. In figure 4.7 the different series represent varying levels of vehicle spacing requirements, while in figure 4.8 the series represent varying levels of maximum vehicle speed. In both figures it is interesting to note that the speed-density relationship is not linear, as Greenshields model assumes for highway traffic. Rather because this model determines conflicts from vehicle speeds and the conflicts in turn determine the reduction in average speed (see section 3.5 above), the relationship between speed and density is curvilinear. Initially at low densities the rate of change in actual speed is low, because the conflict rate does not increase greatly with density. However, as density increases and the conflict rate increases, the actual vehicle speeds will slow more significantly with added density. Ultimately this rate of change will slow again as vehicles slow down, also decreasing the conflict rate given density. This relationship is interesting firstly in that it represents a key difference from previous traffic models that assumed a linear speed-density relationship for highway traffic (Greenshields 1935). In practicality this result is also interesting because it indicates that AAM operators can add aircraft to low density airspace without seeing significant reductions in actual vehicle speeds from conflicts. However, adding vehicles to higher density airspaces will create larger speed reductions that are desirable to avoid.

Based on the theoretical results demonstrated in figure 4.7, it can be seen that traffic flows with larger spacing requirements between aircraft will have lower average actual vehicle speeds at any significant level of density. This is because the larger spacing requirements will create more conflicts between vehicles (see figure 4.4 above). This result emphasizes the benefits of lower spacing requirements.



Figures 4.7 and 4.8. Theoretical actual speed-density relationships for varying spacing requirements (figure 4.7, left) and maximum vehicle speeds (figure 4.8, right).

Figure 4.9 demonstrates the differences in average actual vehicle speed given density for several levels of maximum vehicle speed. At lower densities the faster vehicles will move faster than the slower vehicles, as is obvious. However, at higher densities the difference in average actual vehicle speed becomes less pronounced. This occurs because traffic flows with higher maximum vehicle speeds will create more conflicts (see figure 4.6 above), which in turn reduces the average speeds more than traffic flows with lower maximum speeds.

The theoretical relationship between average actual speed and density for varied heading ranges is displayed graphically in figure 4.9, which shows the actual speed-density relationships based on the model in equation 4.4 for several heading ranges. The theoretical results show that larger heading ranges will create slower actual aircraft speeds, especially at higher densities. This result is due to the generation of large numbers of conflicts in airspace with larger heading ranges. In order to avoid significant reductions in vehicle speeds AAM operators should therefore avoid larger heading ranges and higher densities, and instead create airspace structures that preclude these two conditions occurring simultaneously.

Again the zero degree heading range represents conditions in a fixed-route airspace, while the 360 degree heading range is unstructured airspace. In fixed-route airspace no vehicle conflicts will be generated and vehicles will remain at the same speed across all densities up to the maximum possible density of the fixed-route, when there is no more airspace for aircraft to occupy. In unstructured airspace there will be a sharp decline in the actual aircraft speeds due to density because of the large number of conflicts developed.

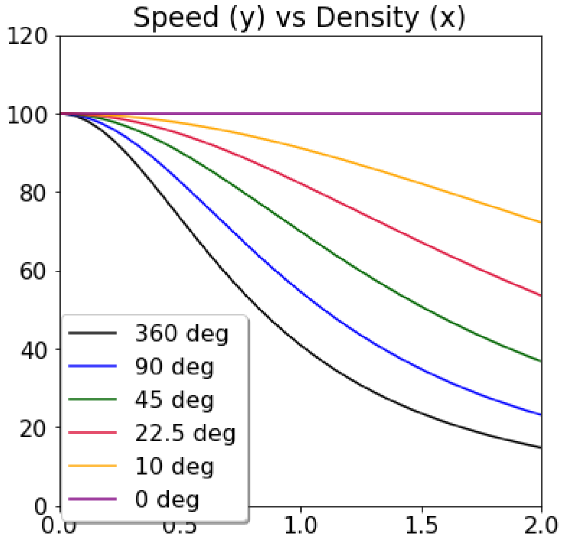
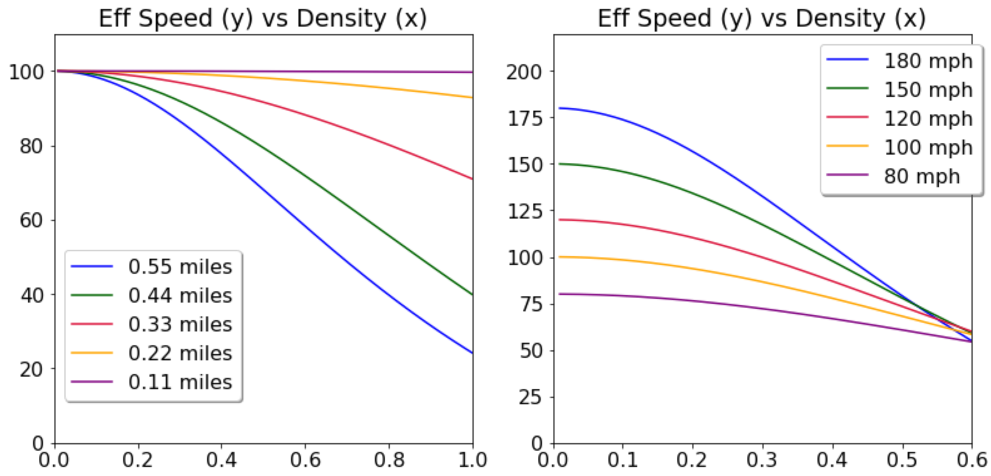


Figure 4.9. Theoretical patterns of actual speeds versus aircraft density in geovectored airspace, with each series representing a different heading range.

Figures 4.10 and 4.11 represent the theoretical effective speed-density relationship that was developed in equation 4.8. The patterns of this relationship are similar to the actual speed-density relationship seen in figures 4.10 and 4.11. In practical terms this is because both actual and effective speeds follow similar patterns of speed reduction as higher densities create more conflicts between aircraft.



Figures 4.10 and 4.11. Theoretical effective speed-density relationships for varying spacing requirements (figure 4.10, left) and maximum vehicle speeds (figure 4.11, right).

The patterns of effective speed relative to density are similar to the patterns of actual speed relative to density in that the marginal change in effective speed at low densities is low due to a low rate of change in conflicts. As densities rise the effective speed is reduced more significantly due to more conflicts being created which require detours to resolve, these detours reduce the effective speed by decreasing the vehicle speed towards its destination. The impacts of spacing requirements and maximum vehicle speeds are also similar, in that larger spacing requirements see lower effective speeds and a sharper decline in effective speeds while higher vehicle speeds see higher effective speeds but a sharper decline in effective speeds. Because effective speed as a measure of speed towards the destination is directly linked to vehicle travel time, these results are particularly meaningful for operators. Higher effective speeds will directly indicate shorter travel times. Higher spacing requirements are related to longer travel times and a sharper increase in travel times, incentivizing operational methods that allow for lower spacing requirements while maintaining safety. Higher maximum vehicle speeds are as expected related to shorter travel times, but also have a sharper increase in travel times due to rising density than lower maximum vehicle speeds. This is notable because it indicates that for high density airspace scenarios operators may end up with similar travel times regardless of maximum vehicle speeds.

The effective speeds of aircraft are also impacted by the allowable heading range. Figure 4.12 shows the relationships between the average effective speed of aircraft and the aircraft density for various heading ranges. Similar to the actual aircraft speed-density relationship larger heading ranges will produce a steeper decline in effective speed at higher densities. This is caused by a higher conflict rate for larger heading ranges at higher densities. Effective speed is important for operators and planners to consider since it directly impacts aircraft travel times through the system. Therefore, to keep system travel times reasonable and decrease the flying time between origin and destination for AAM vehicles, planners and operators should look for airspace structures that do avoid high densities with large heading ranges.

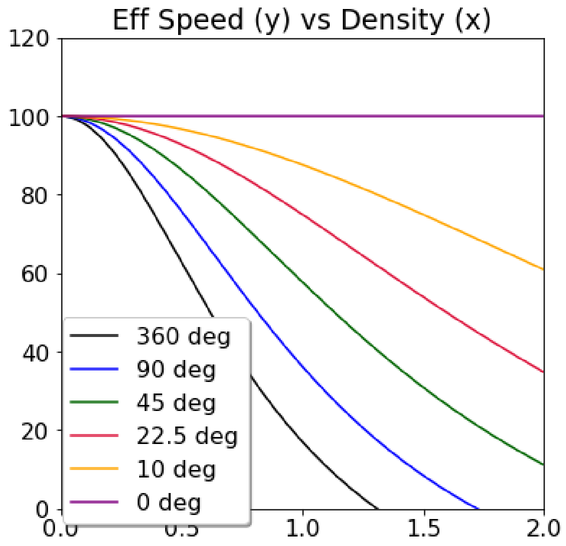
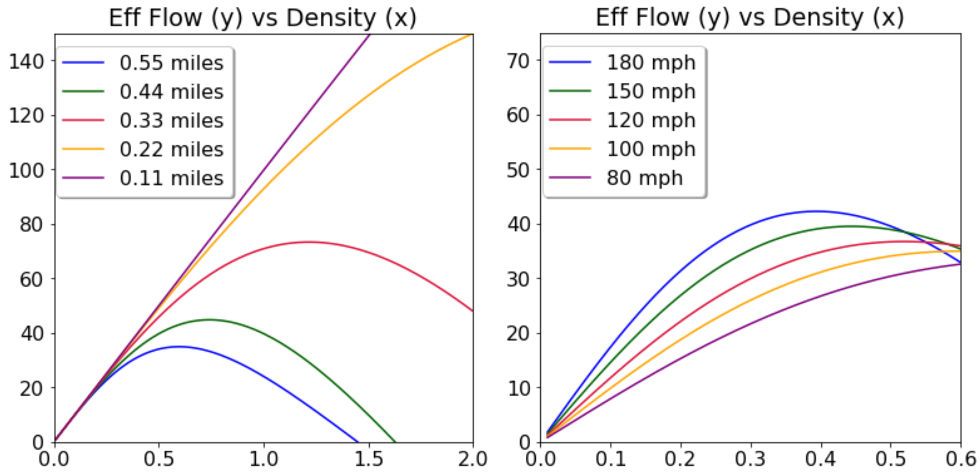


Figure 4.12. Theoretical patterns of effective speed versus aircraft density in geovectored airspace, with each series representing a different heading range.

4.8 Patterns from Traffic Flow Models – Flow Rate

Effective flow rate is a key measure because it measures the output productivity of the airspace, or how the rate at which airspace can process aircraft. The theoretical model for effective flow rate depending on vehicle density was developed in equation 4.12 by joining the effective speed model with density. The patterns of this model are shown graphically in figures 4.13 and 4.14 below. The broad pattern reveals the familiar fundamental diagram from traffic flow models. The fundamental diagram demonstrates that at low densities the flow rate increases proportionally with the density because vehicle speeds are not significantly impacted. However, at higher densities more conflicts are created, which in turn reduces vehicle speeds and decreases the positive rate of change of flow rate given density. Eventually a critical density is reached when the effective flow rate is at its maximum, and further increases in vehicle density actually cause the flow to breakdown and the flow rate to decline. This pattern is manifested in the effective flow rate-density relationship and demonstrates clearly that airspace density must be carefully managed by operators in order to avoid breakdowns in flow that occur at high density. Because there are decreasing returns to density and increases in density increase travel times as previously noted, operators must balance a cost-benefit decision of operating fewer vehicles simultaneously at higher speeds or more vehicles simultaneously at lower speeds. The fundamental diagram depicts the trade-off between density and throughput which forms a key part of that decision.



Figures 4.13 and 4.14. Theoretical effective flow rate-density relationships for varying spacing requirements (figure 4.13, left) and maximum vehicle speeds (figure 4.14, right).

Figure 4.13 also demonstrates the different patterns of effective flow rate developed for varying spacing requirements. At low densities all spacing requirements will have the same effective flow rate because there are few aircraft to create conflicts and slow down vehicles. As densities rise however different spacing requirements cause traffic flows to reach very different critical densities, which greatly impacts the effective flow rate. It is seen in figure 4.13 that larger spacing requirements lead to lower critical densities and lower effective flow rates of aircraft. This further reinforces the previous relationships that demonstrated how reducing the spacing requirements safely can significantly increase the potential traffic flow by encountering fewer conflicts, maintaining higher speeds, and allowing for higher flow rates.

Figure 4.14 similarly shows the flow rate patterns for varying maximum vehicle speeds. At low densities each scenario has a different rate of change in the flow rate because of the different vehicle speeds. From low to high densities the higher maximum vehicle speeds allow for higher flow rates. However, the lower maximum speeds lead to higher critical densities because of the lower rate of conflicts given density. This insight is interesting because it indicates that higher vehicle speeds do allow for a higher throughput of vehicles in airspace, but for high density airspace lower vehicle speeds can operate without reaching the critical density and flow breakdown. Such a finding recognizes that under certain situations with high airspace density operators may actually restrict vehicle speeds in order to avoid reaching a critical density and flow breakdown.

The graphical relationships between effective flow rate and density for multiple levels of heading ranges are shown in figure 4.15. At low densities the throughput of vehicles will be effectively equal for all heading range values since there is not a significant number of conflicts. At higher densities Figure 5 shows that for airspaces with larger heading ranges for aircraft both the maximum flow rates and the critical densities of airspace are lower. This is because aircraft density will create more vehicle conflicts in airspace with larger heading ranges.

The zero degree level of heading range represents the fixed-route airspace, which does not allow for different headings that could cause conflicts and decrease vehicle speeds. However, fixed-route airspaces are constrained by a maximum density of the airspace, beyond which there is no more available space for vehicles, and this density caps the throughput of vehicles. This constraint should be considered when examining these relationships. The 360 degree heading range corresponds to unstructured airspace, in which the critical density and maximum flow rate will be much lower because the conflict rate due to density is much higher in unstructured airspace. In order to maximize throughput of aircraft through a specific section of airspace planners and operators should seek to minimize the heading range and manage the aircraft density.

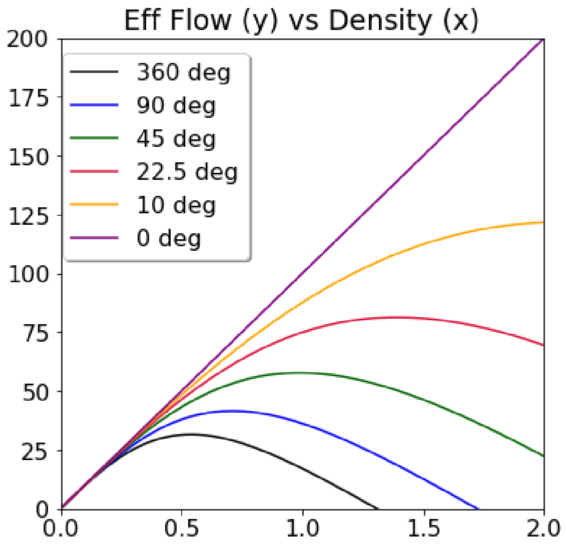


Figure 4.15. Theoretical patterns of effective flow rate versus aircraft density in geovectored airspace, with each series representing a different heading range.

4.9 Simulation Setup

Validation of the theoretical models is an important step. The third objective of this paper is to test the accuracy of the theoretical models and validate their relationships through simulation. Simulated data is necessary for validation instead of observed data because there are currently very few instances of AAM or similar vehicles operating, and none of vehicles operating at high density. The simulator of the motion of AAM vehicles through airspace as described in chapter 3 was used to generate simulated traffic flow data.

Based on the trajectories of aircraft moving through the study volume the traffic flow measures are calculated. Each simulation is run for 5,000 seconds of simulated time, or 83 minutes. The traffic flow measures are aggregated into sets of 300 seconds, or 5 minutes. Multiple simulations were run for each parameter level to better confirm the results and reduce the effects of randomness built into vehicle starting times, origins, destinations, and headings.

4.10 Simulation Results - Conflict Prediction

The conflict prediction model was tested with conflict resolution turned off, but with conflict detection in order to count the number of conflicts. Simulations were performed across multiple levels for each parameter. In addition to conflict counts the density of vehicles in the study airspace was counted and accumulated in the time windows. The conflict-density relationship was then explored by plotting as individual points the average vehicle density in the study airspace during the time window with the number of conflicts occurring in the study airspace. These conflict-density plots are shown in figures 4.16 and 4.17 for multiple parameter levels, with each level colored differently. The theoretical gas law conflict prediction model developed in equations 4.2 and 4.16 were used to independently create predictions of the number of conflicts for the given vehicle density and parameters. The curve of these predictions was overlaid on the scatter plots of simulated data to compare the two. As demonstrated in figures 4.16, 4.17, and 4.18 the theoretical model does an excellent job of both capturing the shape of the conflict-density relationship and predicting the number of conflicts. The R-square values found at each level are generally high. These results indicate an excellent fit for the model with the simulated results and validate the conflict prediction model for unstructured airspace. The plots also confirm that at similar density levels the conflict rates for larger spacing requirements and faster speeds are higher.

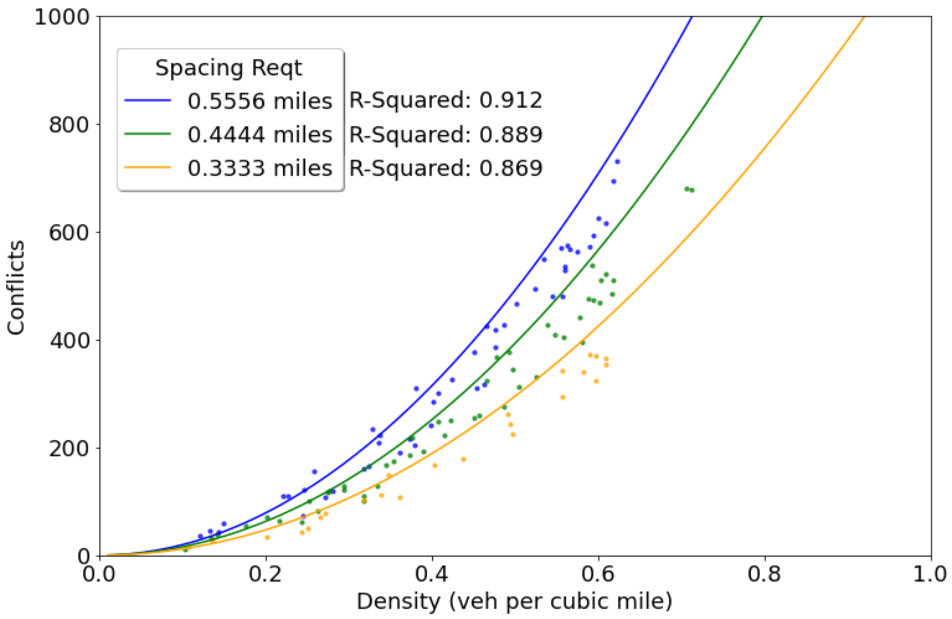


Figure 4.16. Comparison of simulated results (dots) with the theoretical predictions (curves) for multiple spacing requirement levels of the conflict-density relationship.

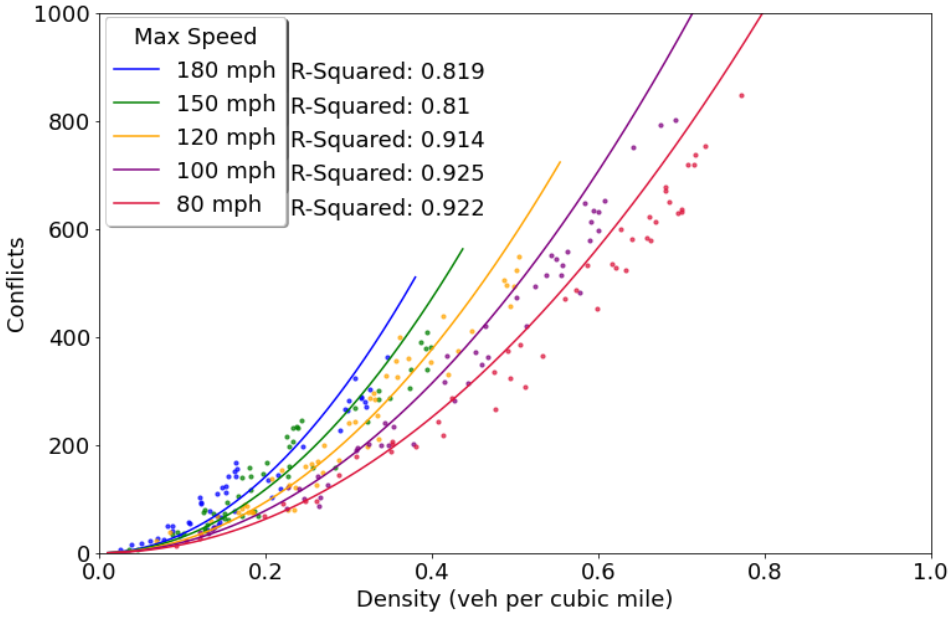


Figure 4.17. Comparison of simulated results (dots) with the theoretical predictions (curve) for multiple maximum speed levels of the conflict-density relationship.

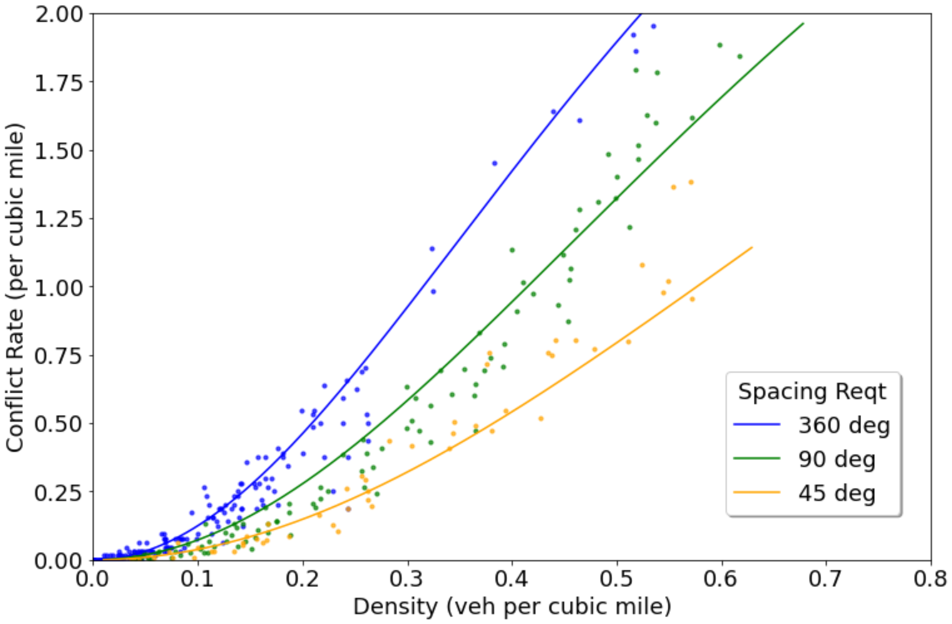


Figure 4.18. Conflict rate versus density of airspace for three allowable heading ranges. Simulated results are shown by points, while theoretical models are predicted by curves.

4.11 Simulation Results - Traffic Flow Models

The remaining three theoretical traffic flow models were each tested against simulated results to validate their relationships. The objectives of this chapter include developing models for a range of vehicle parameters, and therefore the models were tested against a range of vehicle parameters. For each of the vehicle spacing requirements and maximum vehicle speeds five levels were chosen and multiple simulations conducted of the air traffic flow for each parameter level to gather simulated results. These simulation runs were conducted with the same setup as above and with conflict resolution turned on, such that conflict resolution will affect vehicle speeds and traffic flow. The simulated results are again plotted using a scatter plot technique, with each point representing the average traffic measure values of the study airspace during one time window (5 minutes) of the simulation. The theoretical models are then used to predict values using only the density and vehicle parameters. The predicted values are shown as curves overlaid on each figure. As multiple parameter levels are plotted simultaneously, each parameter level is plotted in a different color, with separate R-squared values for only results pertaining to that parameter level calculated and displayed.

To begin with the average actual speed-density model developed in equations 4.5 and 4.17 are tested. The results are displayed in figure 4.19 (testing various spacing requirements), figure 4.20 (testing various maximum speeds) and figure 4.21 (testing heading ranges). From the figures we can see that the theoretical model (represented by the curves) generally does an excellent job of predicting the average actual vehicle speed in the study airspace. The R-squared values generally indicate an excellent fit for the theoretical model compared to the simulated results. The results also confirm the theoretical finding that for multi-dimensional traffic flow the speed-density relationship is not linear, but instead curved with speed reductions at low density not as large as at higher densities. Also, the results in figure 4.19 show that larger spacing requirements will create sharper declines in average vehicle speed from density. For different maximum speeds in figure 4.20 the traffic flows with higher maximum speeds will allow for faster speeds with sharper speed reductions due to density than lower maximum speeds. And lastly in figure 4.21 the larger heading restrictions will create more conflicts and slower speeds for vehicles than smaller heading restrictions.

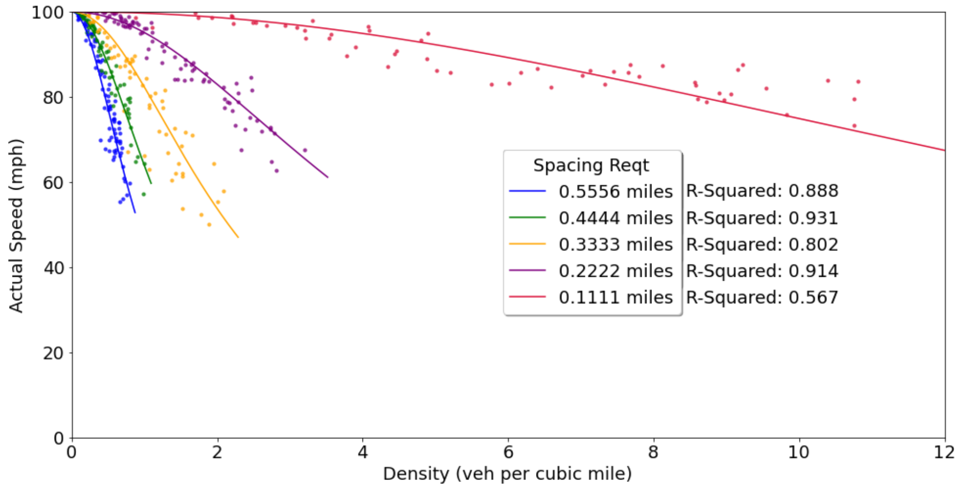


Figure 4.19. Comparison of simulated results (dots) with the theoretical predictions (curves) for the actual speed-density relationship over multiple spacing levels.

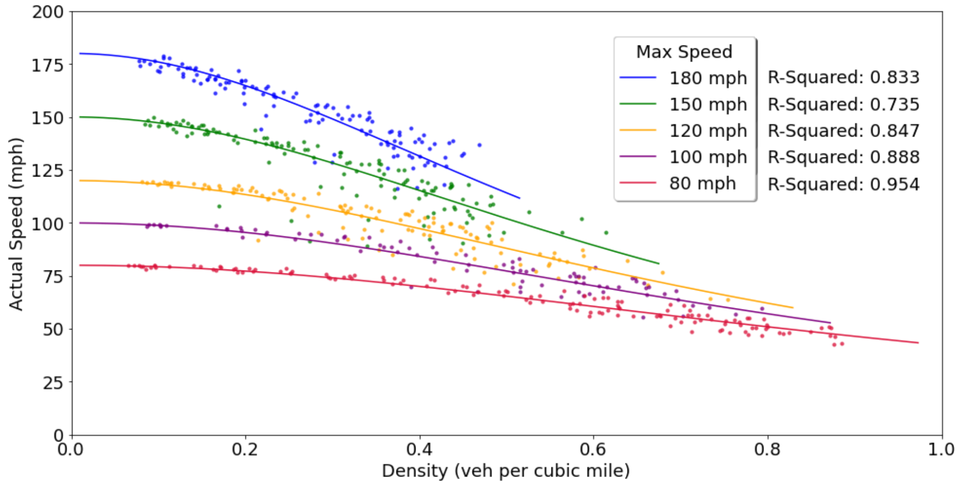


Figure 4.20. Comparison of simulated results (dots) with the theoretical predictions (curves) for the actual speed-density relationship over multiple maximum speed levels.

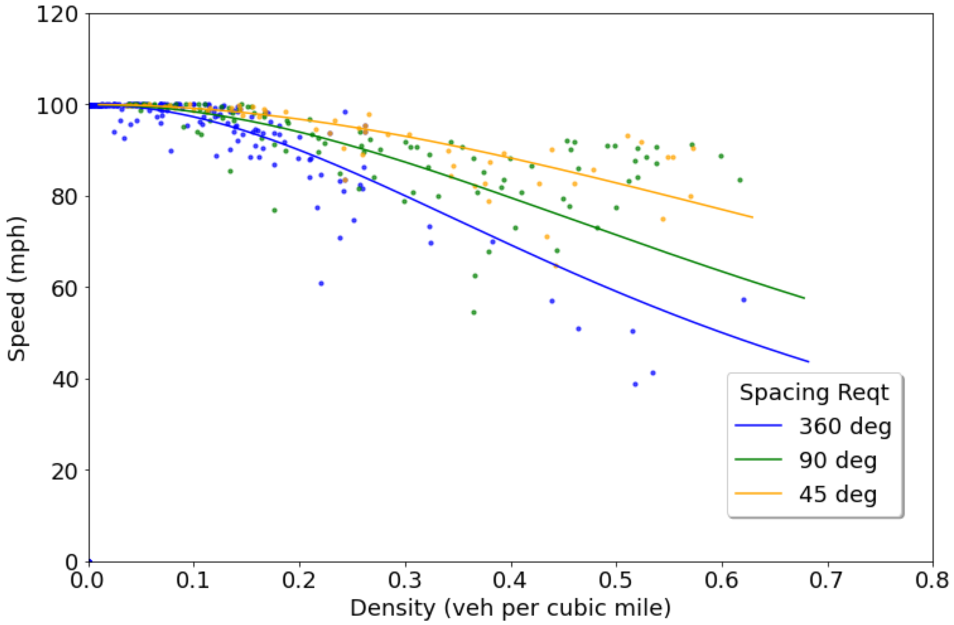


Figure 4.21. A Comparison of simulated results (dots) with the theoretical predictions (curves) for the actual speed-density relationship over multiple heading restriction levels.

Next the theoretical model from equations 4.8 and 4.18 relating the average effective speed to vehicle density was tested based on the same simulated results. The simulated results and theoretical predictions are plotted in figures 4.22, 4.23, and 4.24. As with the actual speed results, the effective speed-density results demonstrate a generally good fit for the theoretical model with the simulated results. The prediction curves closely follow the simulated results points for each of the parameter levels. The R-squared values are also generally high, indicating a good fit. The results in figure 4.22 confirm the theoretical finding that declines in effective speed due to density are larger for traffic flows with larger spacing requirements than smaller ones. In figure 4.23 the results demonstrate that traffic flows with higher maximum speeds do have higher effective speeds at low density, but that these effective speeds converge at higher densities. The varied heading restrictions in figure 4.24 identify that effective speeds will be faster at high densities for traffic flows with similar headings.

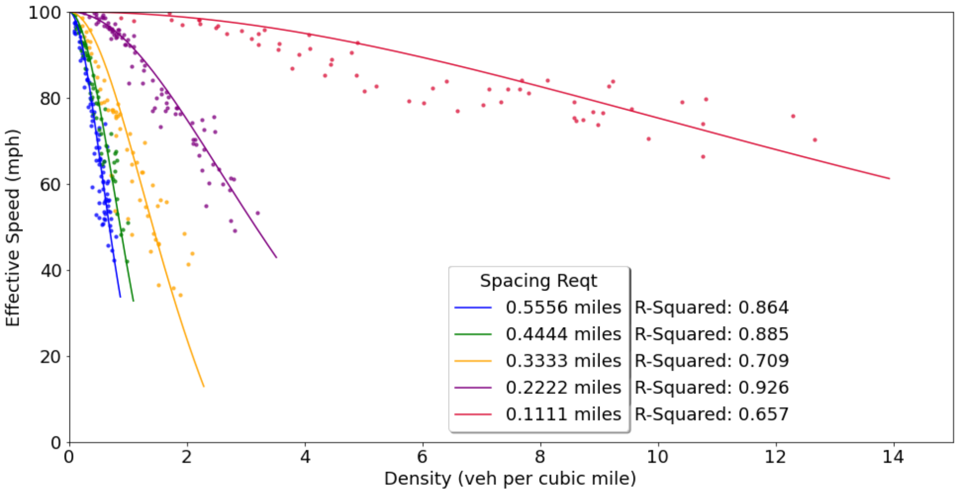


Figure 4.22. A Comparison of simulated results (dots) with the theoretical predictions (curves) for the effective speed-density relationship over multiple spacing levels.

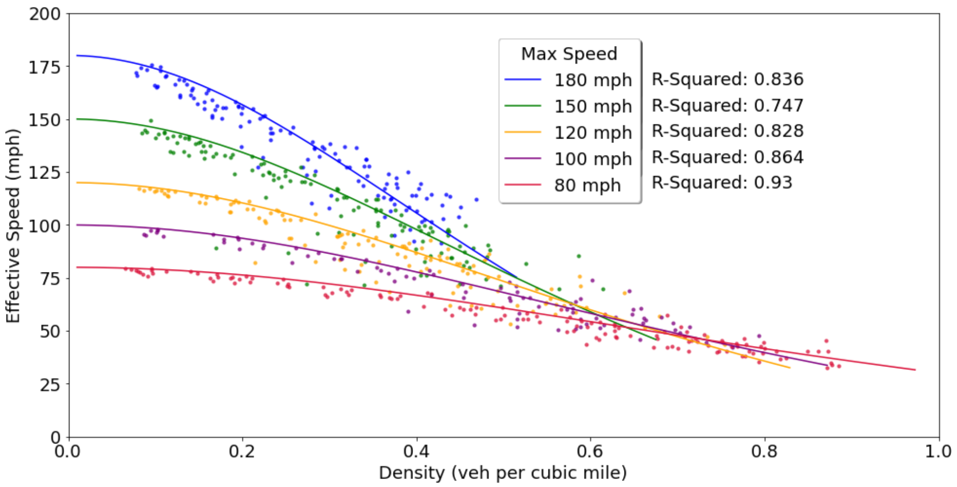


Figure 4.23. A Comparison of simulated results (dots) with the theoretical predictions (curves) for the effective speed-density relationship over multiple maximum speed levels.

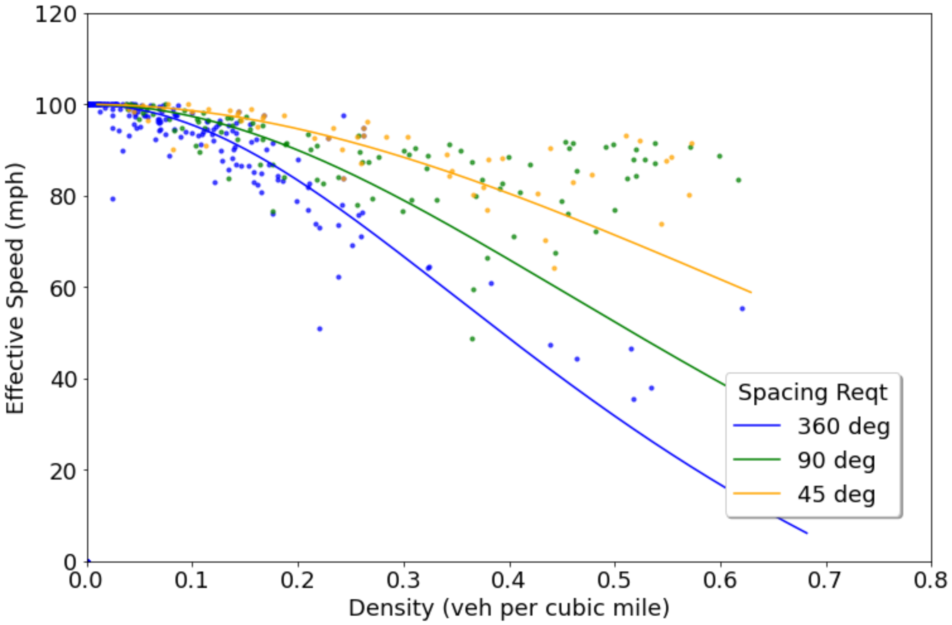


Figure 4.24. A Comparison of simulated results (dots) with the theoretical predictions (curves) for the effective speed-density relationship over multiple heading restriction levels.

Lastly the model of the effective flow rate (or throughput) and density from equations 4.12 and 4.19 were tested. The results for various spacing levels are shown in figure 4.25, various maximum speed levels in figure 4.26, and various heading restriction levels in figure 4.27. In each of the results we find the pattern of the fundamental diagram, in which flow rate increases proportionally with density at low densities before having declining returns to density at higher densities. The presence of critical densities where the flow rate has reached a maximum are also notable. The results in both figures show a good fit with generally high R-squared values for the theoretical predictions and the simulated results. This finding supports the validation of the traffic flow models developed in this paper. It is also demonstrated that for traffic flows with larger spacing requirements there will be a lower critical density and maximum flow rate than traffic flows with smaller spacing requirements. In figure 4.26 it can be seen that higher maximum speeds allow for higher flow rates than lower maximum speeds, albeit with the challenge of a lower critical density. Finally in figure 4.27 smaller heading restrictions that create more similar headings between aircraft are shown to have a higher throughput and critical density than larger heading restrictions.

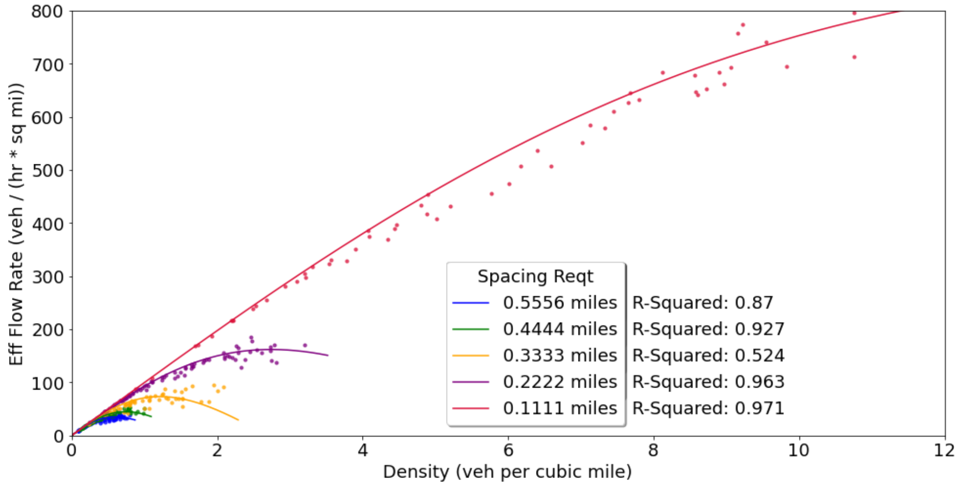


Figure 4.25. Comparison of simulated results (dots) with the theoretical predictions (curves) for the effective flow rate-density relationship.

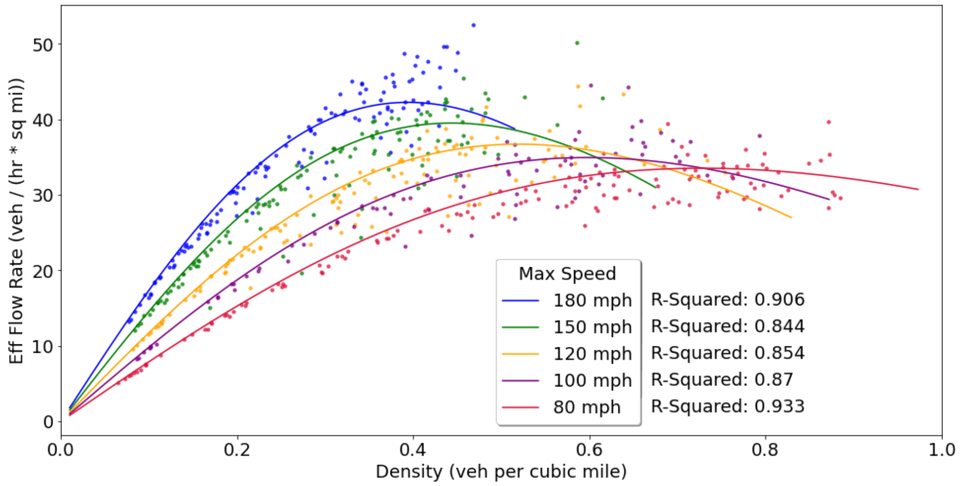


Figure 4.26. Comparison of simulated results (dots) with the theoretical predictions (curves) for the effective flow rate-density relationship.

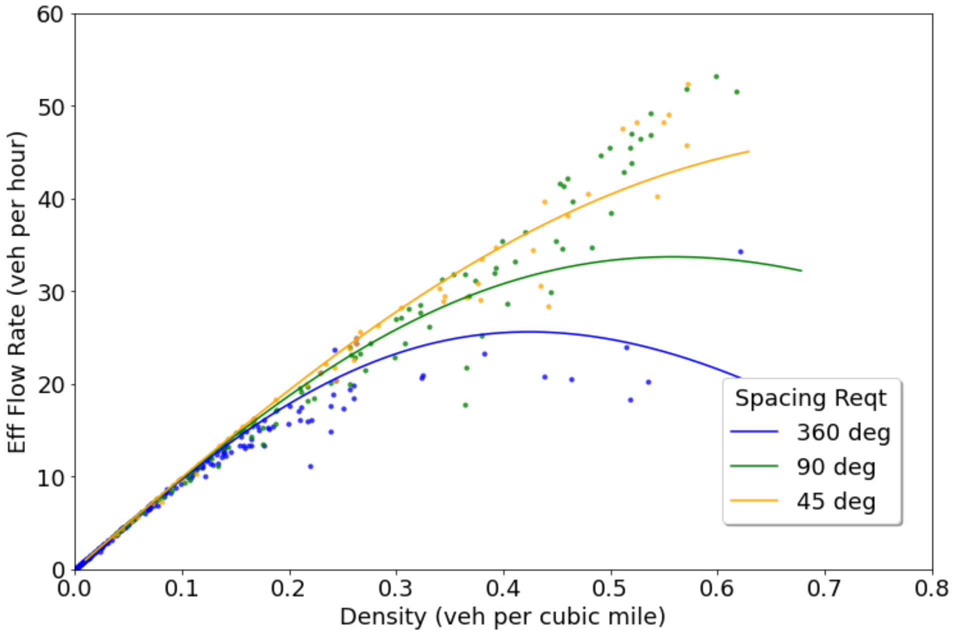


Figure 4.27. Effective flow rate versus density of airspace for three allowable heading ranges. Simulated results are shown by points, while theoretical models are predicted by curves.

Throughout the validation process each of the theoretical models demonstrated a strong ability to predict the traffic flow values produced via simulated results. These results support the validation of the theoretical models and the findings based on the models. They also demonstrate that the models could be used to make predictions based on vehicle densities and parameters for other contexts in which unstructured airspace is used.

4.12 Vehicle Travel Times and Airspace Capacity

Two key operational parameters for AAM service are travel times and airspace capacity. In this section each of these measures are looked at more closely. First the calculation of each is described before graphical representations of the trade-offs between density, operating parameters, and travel times and capacity are shown and discussed.

Travel time describes how long the flight leg of an AAM trip would take, and is important when comparing the level of service to other modes and alternatives. Travel times for AAM are also important when considering that each aircraft has limited charge, and therefore longer travel times run the risk of a forced diversion to a different vertiport in order to recharge. A travel time can easily be calculated for a trip by dividing the distance of the trip by the average speed. In multi-dimensional traffic flows, however, there is a distinction between actual speed and effective speed. Because effective speed measures progress towards the goal, that is the speed that is relevant to travel times. Therefore, travel times can be calculated by dividing trip distance by average effective speed, as shown in equation 4.20. In this equation TT represents the trip travel time (time spent in the cruising phase of flight), d represents the distance of the trip, and e represents the average effective speed of the vehicle.

$$TT = \frac{d}{e} \qquad \text{(Eqn. 4.20)}$$

Airspace capacity in this work is a measure of the maximum throughput of airspace. The capacity of airspace is a key constraint for AAM planners and operators to work with, since it limits the number of trips that can be undertaken simultaneously. Previous research has attempted to measure airspace capacity by the maximum number of simultaneous flights before a safety threshold was crossed (Bulusu 2019, Vascik et al. 2020) or the conflict rate accelerated unsustainably (Jardin 2004, Sunil et al. 2018a). The safety threshold method commonly determines a number of flights that can be safely managed by human (or autonomous) ATC operators and uses that as the airspace capacity. However this capacity is restrained by the abilities of the ATC system. Meanwhile Jardin (2004) proposed the “domino effect parameter” (see section 2.6) for use in determining a capacity at which the conflict rate would be unsustainable. While this system does consider conditions in the traffic flow, it does not strictly maximize the throughput of the airspace. The definition of airspace capacity used here as the maximum effective flow rate of vehicles through airspace represents a new measure of airspace capacity that is focused on maximizing throughput. Airspace capacity can be calculated by first calculating the critical density of flow rate and then using that critical density to calculate the maximum effective flow rate possible.

The trade-offs between density, effective flow rate, travel times, and operational parameters are explored in figures 4.28 (spacing requirements), 4.29 (maximum aircraft speeds), and 4.30 (heading restrictions). Default scenario values were used unless otherwise noted, which includes a 100 mph maximum aircraft speed. The travel time for a default vehicle at 100 mph experiencing no conflicts or diversions was set to be 10 minutes, therefore the travel times refer to the time to complete a 16.67 mile trip. The independent variables in each figure are again density, demonstrating the impacts of rising vehicle densities on traffic flow and travel times. The dependent variables on the y-axis are effective flow rate (in the solid color curves) and average travel time (in the dotted curves).

Figure 4.28 demonstrates the general shapes of the relationships. The effective flow rate versus density relationships follows the fundamental diagram. The maximum point on these curves represents the critical density and the airspace capacity, as defined by the maximum throughput of vehicles. The travel time versus density curves represent an exponential growth in travel times as density increases. In low density scenarios adding marginal density has very little impact on travel times, however in high density scenarios a marginal density addition can add many minutes to the average travel times. Operators will want to keep travel times low, and therefore it is important to manage aircraft density. However, operators will also want to maximize throughput in the airspace which does require adding density until the critical density is reached.

There are three spacing requirements represented in figure 4.28 by different colors. The largest spacing requirement (0.55 miles shown in blue) demonstrates consistently lower throughput and capacity and higher travel times than smaller spacing requirements at medium and high densities. This result reinforces the previous results that smaller spacing requirements are useful for traffic flow in terms of allowing more throughput and faster speeds that lower travel times.

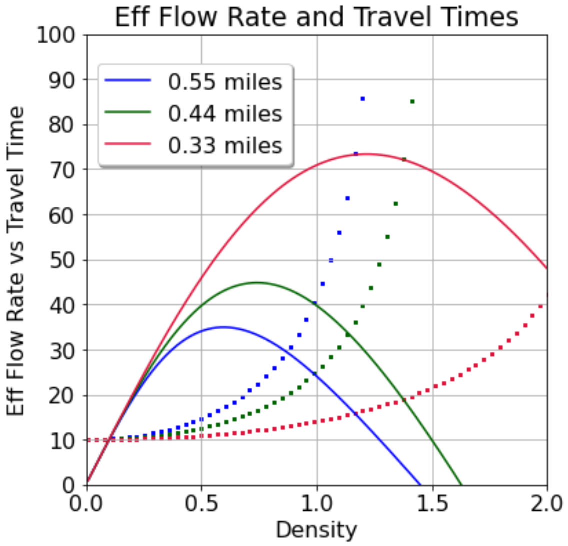


Figure 4.28. Effective flow rate (solid curves) versus average travel time (dotted curves) for three levels of spacing requirements.

Comparing travel times, capacities, and maximum vehicle speeds in figure 4.29 also provides some insights on managing traffic flow. Section 4.8 first pointed out that faster vehicle speeds would allow for higher throughput and capacity than slower vehicle speeds, but at a lower critical density. This trend again is represented in the effective flow rate curves in figure 4.29 (shown as solid curves). The effect on travel times is similarly mixed. While faster maximum speeds allow for shorter travel times at lower densities, the travel time curves converge and cross at higher densities, creating a scenario where slower maximum speeds lead to shorter travel times in highly congested scenarios. This evidence supports using speed restrictions for heavily congested airspaces in order to reduce the conflict rate. However, the patterns also suggest this method may only be useful after flow breakdown has been reached (beyond the critical density). In such a scenario restricting the maximum vehicle speed could actually shorten the travel times.

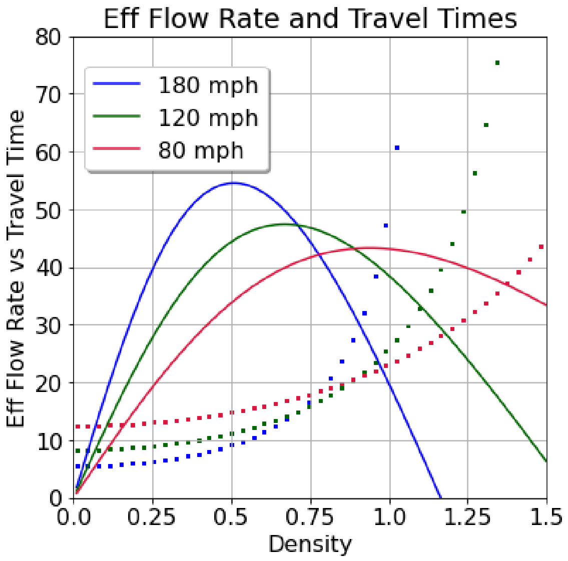


Figure 4.29. Effective flow rate (solid curves) versus average travel time (dotted curves) for three levels of maximum vehicle speeds.

Similar patterns can be observed in figure 4.30 when comparing airspace capacities and travel times of varying heading range restrictions. At low densities the travel times do not vary greatly among airspace with different heading range restrictions, but at higher densities the airspaces with more similar headings and smaller heading ranges see shorter travel times. Similarly, the smaller heading ranges have a higher airspace capacity and critical density than larger heading ranges. These findings support the insights from the previous results that restricting airspaces to aircraft with similar headings can increase airspace throughput and capacity and decrease travel times by lowering the conflict rate between aircraft.

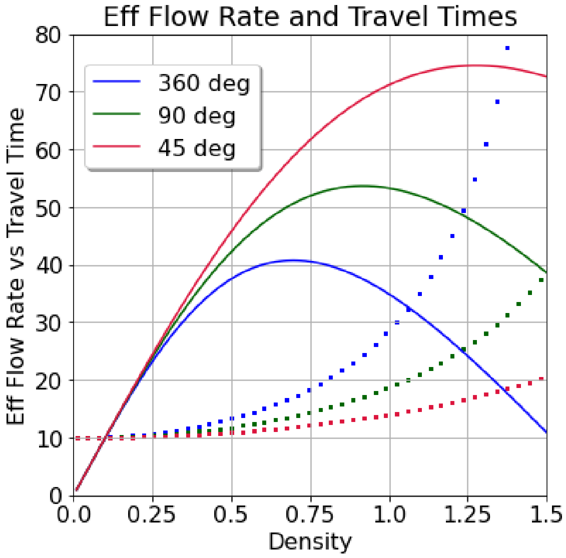


Figure 4.30. Effective flow rate (solid curves) versus average travel time (dotted curves) for three levels of heading restrictions.

4.13 Implications of Traffic Flow Models

The theoretical results of the models developed herein were discussed in detail on a model-by-model basis in sections 4.2 through 4.5. However, there are broader implications that are worth considering across models. Perhaps the biggest implication of the traffic flow models developed in this paper and the previous work (Tereschenko et al. 2020, Sunil et al. 2019a] is the critical role of vehicle density in air traffic flow. Vehicle density is directly related to the number of conflicts in airspace, and the number of conflicts greatly impacts the speeds, trajectory shapes, and flow rates that comprise the traffic flow. Equation 4.2 and figures 4.4 through 4.6 demonstrated the power relationship between vehicle density and conflict rate, with conflict rate increasing much more quickly at higher densities than lower densities. The actual speed-density, effective speed-density, and effective flow rate-density models built on this relationship and demonstrated the importance of vehicle density. As density increases vehicle speeds decline, increasing travel times and decreasing the returns to flow rate of density. Given these relationships aircraft density is a key measure for airspace that should be closely considered by operators and planners and managed during operations.

A second key implication from this work is the impact of vehicle spacing requirements on traffic flows. The conflict prediction model included and illustrated how spacing requirements are a factor in the conflict rate, and therefore a key parameter to consider in the subsequent traffic flow models. The theoretical results considered varying spacing requirements and demonstrated: 1) that larger spacing requirements have a higher conflict rate at any specified density, 2) that larger spacing requirements lead to lower average speeds and sharper declines in speed, and 3) that larger spacing requirements do not impact the throughput of airspace at low densities, but at higher densities have lower throughput and lower critical densities. In total these results indicate that operators and planners should seek to minimize the spacing requirements while ensuring safety, as the benefits include fewer conflicts, lower travel times, and higher flow rates.

Third are the interesting implications of maximum speeds affecting traffic flows. The gas law model and equation 4.2 demonstrate how higher vehicle speeds cause higher conflict rates at the same density by effectively having aircraft search more airspace for conflicts. The higher conflict rate associated with higher speeds means that while higher maximum speeds do relate to higher average speeds, the average actual and effective speeds both decrease at a faster rate. Therefore one might expect only a small difference from higher maximum speeds in observed travel times at higher densities. In relation to the effective flow rate higher maximum speeds did create higher throughputs at both low and high density. However, higher maximum speed scenarios reached a critical density lower than the critical densities of lower maximum speed scenarios. Taken together these findings reflect that higher maximum speeds may generally be better for lower travel times and higher throughputs. Yet, in high density airspaces the differences in these metrics may be small and operators may favor restricted speeds that decrease conflicts and increase the critical density before the traffic flow breaks down.

The findings in this chapter also suggest that airspace structure, namely restricted airspace headings, may be an effective means for managing air traffic flow at high density. The restricted headings were constructed to consider three types of airspace structure in terms of the allowable range of aircraft headings: unstructured (no restrictions on aircraft headings), geo-vectored (range of aircraft headings), and fixed-route (zero degree range of aircraft headings). It was found that larger aircraft heading ranges experienced more conflicts, lower speeds, and lower aircraft throughput, especially at high densities. Therefore, geo-vectored airspace with small heading ranges and fully-restricted, one-dimensional fixed-route airspace would be expected to have the fewest conflicts, highest speeds, and highest throughputs. These relationships are especially significant at higher levels of densities, where speeds decline and traffic flow breaks down. An effective means for managing a high-density airspace could be to restrict the aircraft headings to protect the traffic flow by reducing the conflict rate of aircraft. In this way it would be possible to maintain higher aircraft speeds and throughputs at higher densities compared to unstructured airspace. Higher speeds and throughputs would indicate that more vehicles could pass through the airspace in lower travel times, effectively reducing airspace congestion restraints for AAM operators.

Based on these findings it might make sense to structure all airspace to a high degree in order to reduce the conflict rate everywhere. But that solution might ignore the trade-off when introducing more structure to airspace. By introducing more airspace structure the mobility of aircraft is restricted, and at a network level the ability of aircraft to route directly to their destination is reduced. In an unstructured system of airspace aircraft are able to route in the most direct way possible to their destination, but in a highly-structured network, aircraft must instead route indirectly through a system of links or zones to arrive at their destination. Thus the context of airspace becomes important when determining an airspace structure. The models in this paper suggested that air traffic flow at low densities was not greatly impacted by the heading restrictions, and therefore airspaces with low expected densities could benefit the most from lower degrees of airspace structure. Meanwhile the models found that at high densities restrictive heading ranges were crucial to maintaining aircraft speeds and throughputs, and therefore airspace with high expected densities may require high degrees of airspace structure. The work in subsequent chapters will explore at local and network levels the appropriate use different degrees of airspace structure considering the expected level of aircraft density in each zone of airspace.

Lastly, the simulated results validated the relationships described in the theoretical models and demonstrated an ability to predict traffic flow measures. Validating the theoretical models is key to applying the findings of the theoretical models. The simulated results across a number of runs and different parameter levels supported the theoretical findings by demonstrating similar patterns and a good overall fit of the theoretical model with the simulated results. Furthermore, after demonstrating a good fit between the theoretical models and simulated results, it is possible to use the theoretical models for air traffic flow predictions in a given unstructured airspace context. The ability to predict with accuracy the state of the air traffic flow without the need for computationally intensive simulations can greatly aid the jobs of AAM developers, operators, and planners. Additionally, other modelers of AAM systems can incorporate these relationships into their work for good approximations of air traffic flow given a set of conditions.

4.14 Chapter Summary

This chapter has developed theoretical air traffic flow models that relate vehicle density and spacing and speed parameters to traffic flow measures for unstructured airspace and the AAM context. The chapter recognized the key role of conflicts in air traffic flow and related vehicle density to the number of conflicts in airspace using a gas law conflict prediction method. The number of conflicts was then related to vehicle speeds using an average speed loss per conflict value. The effects of the speed reductions were then coupled with density to explore the fundamental diagram between flow rate and density. The accuracy of the theoretical models were tested and validated with simulated results for a number of parameter levels. The theoretical and simulated findings were used to provide operational and policy insights for AAM operators, planners, and modelers.

There are several key insights offered by this work. First is the critical role of aircraft density in air traffic flow. The conflict prediction model demonstrated a power rule for the number of conflicts based on density, indicating that at higher densities the conflict rate increases much more quickly. Density was also shown to decrease actual vehicle speeds, effective speeds, and throughput due to conflict resolutions. Based on this finding AAM operators and planners will need to closely manage the airspace density of AAM vehicles to avoid large numbers of conflicts simultaneously and maintain acceptable travel times and throughputs. Second is the importance of the aircraft spacing requirement. The theoretical models found and the simulated results supported that larger spacing requirements have higher conflict rates, sharper reductions in speed from density, and lower critical densities than smaller spacing requirements. Therefore, AAM operators and planners may wish to find the minimal spacing requirements that still allow for safe operations. Third was that aircraft speeds do have a somewhat nuanced role in air traffic flow. As might seem obvious, higher maximum vehicle speeds related to higher average vehicle speeds but they also created a higher conflict rate, lower critical density, and showed a sharper reduction in vehicle speeds that led to a convergence of speeds at high density. From these findings AAM operators and planners might conclude that vehicle speed restrictions are appropriate in high density scenarios to avoid large numbers of conflicts and a lower critical density. Lastly, the results indicate that the range of allowable aircraft headings in airspace has a significant impact on the conflict rate of aircraft and also the traffic flow. It was found that larger allowable aircraft headings in a zone of airspace increased the relative velocity of aircraft and created a higher conflict rate at a given density. In turn the higher conflict rate decreased the actual and effective vehicle speeds in the airspace and decreased the returns of density for aircraft throughput. The airspaces with higher heading ranges had lower maximum flow rates and lower critical densities than airspaces with lower allowable heading ranges. Based on these results it was found that for a predefined zone of airspace tighter restrictions on headings better protected the air traffic flow from conflicts caused by density. The impact of heading restrictions was greatest at higher aircraft densities. By this measure fixed-route airspace will perform best when protecting air traffic flow at the highest densities, while geovectored and unstructured airspaces may also work well at lower densities.

There were several limitations in the methodology of this chapter. The first is that while the theoretical models went farther than previous work in reducing the reliance on calibrated values, there is still a need to calibrate the average speed loss per conflict value. It is possible though to calibrate this value as a function of parameters such as spacing and maximum speed to reduce the number of contexts requiring calibration. The models used here and the means of producing simulated results was also limited to only two-dimensions. This simplification was made to approximate flying conditions in which an aircraft largely avoids expensive altitude changes and reduce computation times, however it does not completely reflect the ability for aircraft to make altitude changes. The simulator used is also a simple AAM simulator that does not account for the physics and accelerations of aircraft, reducing the accuracy of individual aircraft trajectories. However, the broader trends of air traffic flow are still applicable to this situation.

Chapter 5

In chapter 4 air traffic flow models were developed. These models create a better understanding of air traffic flows and the factors impacting it, allowing for improved operating and planning decisions. The models and results of the chapter highlighted the importance of density, conflicts, and speed reductions for air traffic flow. Also important were operating contexts such as spacing between aircraft, speeds of aircraft, and the similarity of aircraft headings. The air traffic models developed, however, were aimed at unstructured airspaces or geo-vectored airspaces. Numerous AAM concepts have suggested that more structured airspaces such as corridors be used during the introduction of AAM service and for urban airspaces. Several NASA and FAA ConOps documents (FAA 2020, Johnson and Larrow 2020, Price et al. 2020) have proposed and assumed restricted corridors of AAM-specific air traffic at low altitudes. Restricted airspaces are generally proposed for one of two reasons: 1) to deconflict air traffic by ensuring separation between aircraft, or 2) to keep aircraft away from sensitive areas on the ground such as temporary flight restrictions (TFRs) or obstacle avoidance. The proposed corridor flight restrictions offer a way to separate AAM traffic from other aviation traffic and manage the locations that AAM services operate in. These considerations are especially important for AAM because AAM aircraft could be operating in close proximity to other AAM aircraft, the ground, and urban features.

With the understanding that airspace restrictions will be part of an AAM network, it is important to consider how airspace restrictions will impact air traffic flow. The primary objective of this chapter is to develop insights of how airspace structures impact air traffic flow at the local level, including structures' abilities to deconflict traffic along with effects on vehicle speeds and throughput. Chapter 6 then considers airspace restrictions' impacts at the network level.

Airspace restrictions create a geometry of available airspace that is very specific and context dependent, while being critically important to the flow of aircraft through that airspace. These varied and unique contexts make it difficult to develop generalized models of air traffic flow such as those in chapter 4. For example, air traffic flow in an intersection of two restricted corridors would depend on the direction of traffic in the corridors, the angle of intersection, the width of the corridors, and the extent of mixing of aircraft trajectories. All of these considerations would depend on the geometry of the airspace structure specific to the context, and therefore it would be difficult to develop a meaningful generalized model of air traffic flow in all airspace intersections. However, the same key concepts and insights developed in chapter 4 still apply to restricted airspaces, just in different ways. Within that intersection of corridors higher aircraft density will still generate conflicts, conflict resolution will still decrease aircraft speeds, and the speed and density of traffic will still determine throughput.

Because the same air traffic flow concepts still apply, air traffic flow in restricted airspaces are studied in this chapter in much the same way as chapter 4: through aggregated measures of air traffic flow that reveal patterns and relationships from which insights can be gleaned. A series of airspace structures are constructed and air traffic flow through them simulated with the simulator outlined in chapter 3 and compared. However, because of the context dependence of traffic in restricted airspaces, generalized predictive models of air traffic flow are not developed, and instead the relationships between traffic flow variables are studied using models fitted to simulated data. Nine experiments are conducted by comparing simulated air traffic flow results, grouped into four categories of airspace structures: corridors (section 5.2), intersections (section 5.3), bottlenecks (section 5.4), and sporadic restrictions (section 5.5). The specifics of each airspace structure and experiment are included as appropriate within these sections.

5.1 Measurement of Air Traffic Flow in Restricted Airspaces

The macroscopic traffic flows in the experiments of this chapter are measured using the metrics defined in section 3.2. These metrics include conflicts, density, actual speed, effective speed, and effective flow rate. Measures are aggregated for all vehicles within a defined airspace and time window to give a macroscopic understanding of traffic flow in that volume. An important consideration when measuring air traffic flow is where and when to measure, or what study volume to use and for what time window. The answers are generally determined by what is being measured. The study volume and time window should adequately sample the air traffic flow in question by encompassing a significant portion of the air traffic flow as it occurs. However, study volumes should not become too large and capture extraneous airspaces, since this would add unintended values to the sample. This concept is especially important for structures of restricted airspace, such as the corridors concepts explored in this chapter, that do not utilize all areas of an airspace. Instead, some airspace is left inaccessible to aircraft for clearance around obstacles, as buffer between aircraft, or to organize air traffic flow. A study volume that encompasses the entire airspace network including inaccessible airspace would witness unusually low density values because empty airspace is included in the sample. Figure 5.1 shows the top-down view of a single corridor of usable airspace in between two restricted airspaces (red areas) that connects two regions of unstructured airspace with vertiports (black squares). The study volume (blue outline) in Figure 5.1 encompasses a large airspace network, including unusable restricted airspace. By including restricted airspace the density values are deflated, and therefore all traffic flow relationships involving density will be incorrect. In Figure 5.2 the study volume is restricted to only airspaces usable by aircraft within the airspace network, but it is important to note that this volume captures and averages traffic flow both inside and outside the corridor. Figure 5.3 demonstrates an appropriate study volume for an accurate measure of traffic flow within the corridor.

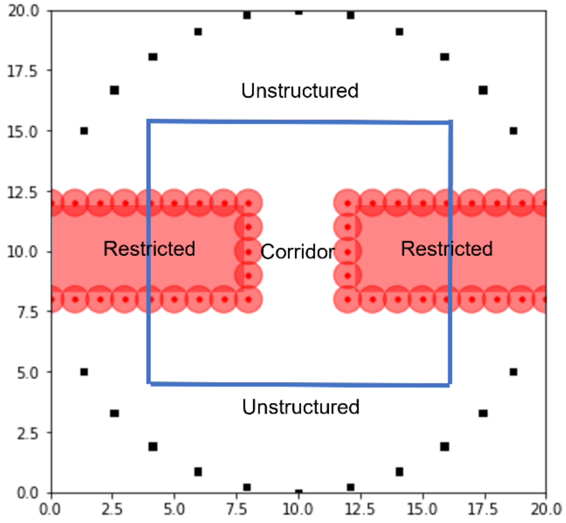


Figure 5.1. Top down view of a study volume (blue outline) measuring traffic flow in the airspace. This study volume is incorrect because it includes unusable, restricted airspace, which will distort measures of density in the airspace.

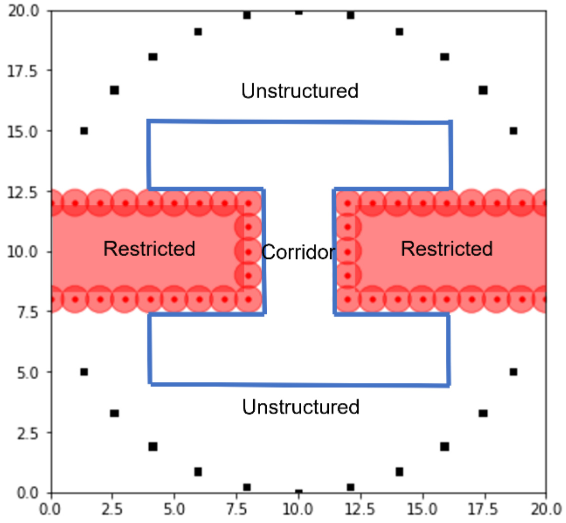


Figure 5.2. Top down view of a study volume (blue outline) measuring traffic flow in the airspace. While this study volume is correct for measuring the corridor and some of the unstructured airspaces, it does not capture the corridor airspace only.

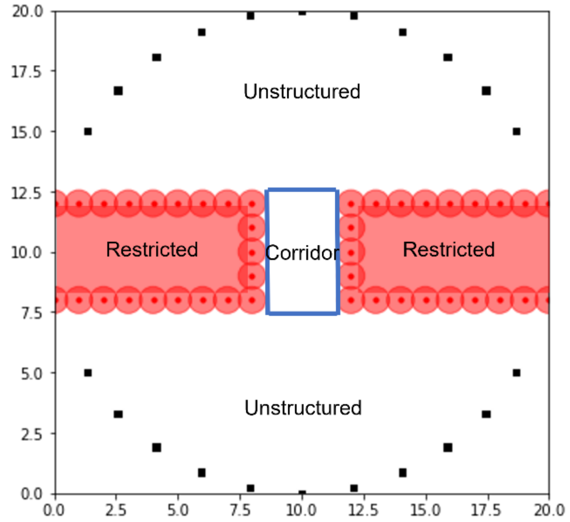


Figure 5.3. Top down view of the correct study volume (blue outline) for measuring traffic flow in the airspace corridor.

The remainder of this chapter explores air traffic flow in specific airspaces around or within airspace structures. Each scenario specifies which airspaces within an airspace structure are included in measurement. Knowing what is included is important for interpreting the results and discerning accurate insights. Using the measurement methods of traffic flow established in section 3.2 and here in section 5.1, it is possible to find results and analyze the macroscopic air traffic flow in airspace structures. The next section begins to explore air traffic flow within corridors of airspace, with subsequent sections looking at intersections of corridors, bottlenecks, and vertiport networks.

5.2 Air Traffic Flow in Corridor Airspaces

Corridor airspaces are defined lengths of accessible airspace with restricted airspaces along the sides of the corridor. AAM-specific corridor airspaces have been proposed by NASA and the FAA (FAA 2020, Johnson and Larrow 2020, Price et al. 2020) as an airspace structure that can allow for AAM service while ensuring separation from other types of aircraft and sensitive areas on the ground. Under this vision, vertiports would be connected by a network of restricted corridors. The setup within each corridor may vary. A corridor could be composed of one or more fixed routes for aircraft to follow, or allow aircraft the freedom to maneuver within the corridor. Within the experiments in this section aircraft are given the freedom to maneuver within the corridor. A corridor could also encompass bidirectional or unidirectional travel.

The first research question about corridor airspaces to consider is how air traffic flow within corridor airspaces differs from unstructured air traffic flow. In chapter 4 it was found that aircraft with similar headings generated fewer conflicts from density. Considering that a corridor will align aircraft headings, we would expect to see fewer conflicts for aircraft within the corridor. In the simulator a unidirectional corridor (without fixed routes) was constructed with restricted airspaces to either side and air traffic flow measured within the corridor, see Figure 5.4a. In figure 5.4a the black squares represent vertiports, the red circles represent the boundaries of accessible airspace, the multi-colored tracks of dots represent a sample of aircraft trajectories, the green arrows depict the direction of traffic flow, and the blue rectangle delineates the study volume. Air traffic flow was simulated through this corridor several times, and the traffic flow measures observed are represented by the blue series of dots and curves in figures 5.4b-f. For comparison simulated air traffic flow data was also measured for unstructured airspace without restrictions, and these results are represented by the green series.

For each of the traffic measure relationship plots in figures 5.4b-f it is first notable that the shapes of each relationship are similar for both the structured corridor and unstructured airspace. These similar patterns are indicative that the same air traffic flow concepts developed in chapter 4 for unstructured airspace apply in restricted airspace. Accordingly, it is expected that higher aircraft densities in corridors will generate more conflicts. The conflicts in turn will reduce aircraft speeds, and the reduced speeds will impact throughput.

Figure 5.4b compares the conflict rate (ratio of conflicts to volume of airspace) with density for both the unidirectional corridor and unstructured airspace. As expected, the air traffic in unstructured airspace generated more conflicts at a given density relative to air traffic in a corridor. This occurs because the aircraft headings in unstructured airspace are not aligned, raising the probability of in-crossing conflicts between aircraft trajectories. Given this result and the concepts explored in chapter 4, it might be reasonable to expect the corridor to demonstrate improved traffic flow at density relative to unstructured airspace in the form of higher average aircraft speeds and higher throughput. However, instead the corridor demonstrates *lower* average aircraft speeds and throughput in figures 5.4c (actual speed vs density), 5.4d (effective speed vs density), and 5.4f (effective flow rate vs density). If there are more conflicts generated in unstructured airspace, and each conflict reduces aircraft speeds and slows throughput, how can the unstructured airspace perform better?

Figure 5.4e offers an answer. This figure compares the average effective aircraft speeds with the conflict rate. For the two types of airspace in this comparison, figure 5.4e clearly shows that the corridor airspace experiences larger reductions in effective speed for each conflict. This trend suggests that conflicts in the corridor constructed are more difficult to resolve than conflicts in the unstructured airspace. While the aircraft do have freedom to maneuver within the corridor, the accessible airspace in the corridor is highly restricted, offering little space for aircraft to detour around potential conflicts. Therefore when conflicts do occur, they incur longer detours and delays because of the restricted set of available airspace in which to detour. Unstructured airspace has no such restrictions, allowing aircraft greater freedom when finding a conflict resolution. Considering the narrow corridor constructed for this scenario, it is possible that a wider corridor with greater maneuverability would not have these issues to the same extent. However, this scenario highlights an important consideration for air traffic flow in restricted airspaces. When evaluating the structured airspace both the similarity of headings between aircraft and the maneuverability to resolve conflicts with short delays or detours must be considered.

The results of the comparison between a unidirectional corridor and unstructured airspace find that while corridors may be effective at limiting the conflict rate between aircraft, limited maneuverability in the corridor can pose its own challenges to air traffic flow. Even a small number of conflicts in a restricted corridor could greatly decrease the aircraft speeds and impact throughput, creating longer travel times and lower capacity in the airspace. Unstructured airspace, although it generates more conflicts, may also prove more resilient to conflicts. When considering the widespread use of corridors for AAM service as has been proposed by NASA and the FAA, this challenge with resolving conflicts should be understood and planned for.

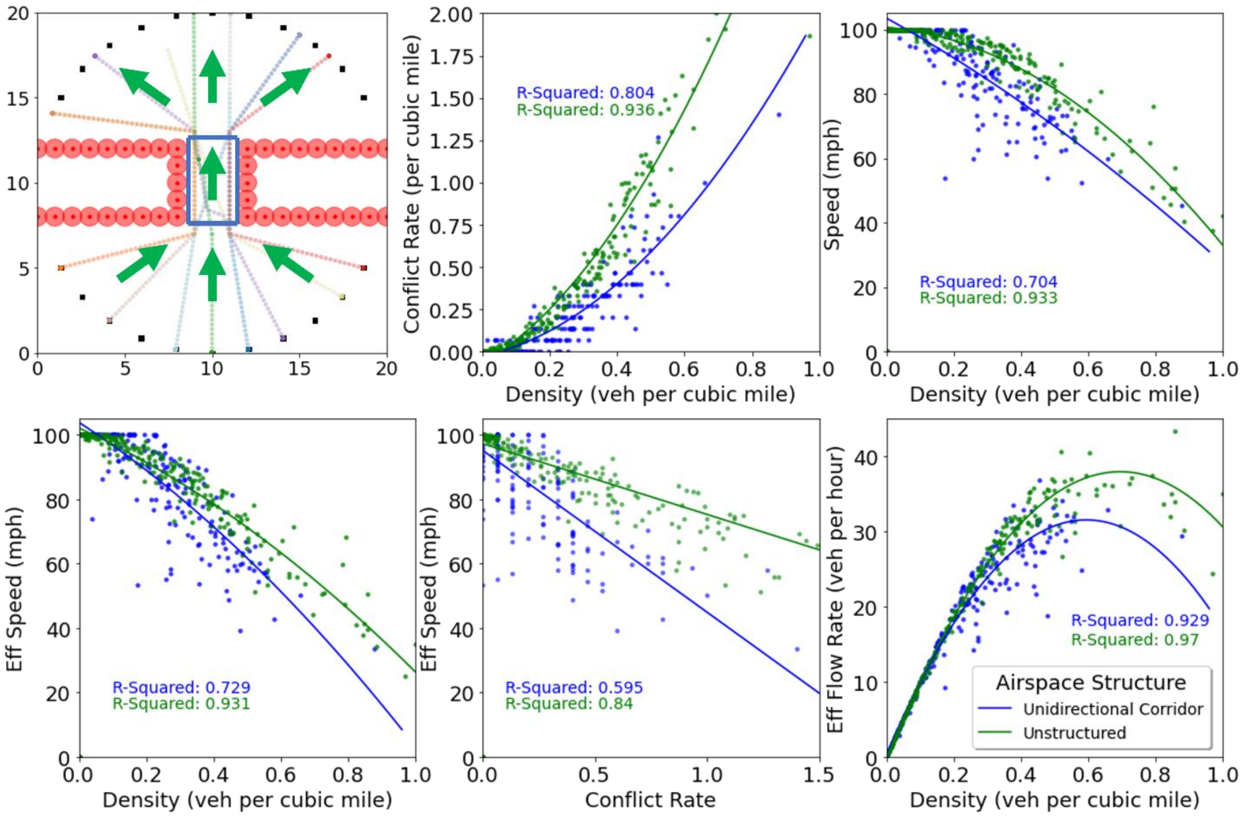


Figure 5.4 a (top left) - f (bottom right). a depicts the unidirectional corridor airspace scenario considered. b through f compare key traffic flow measures for the unidirectional corridor (blue) and unstructured airspace (green).

Corridors can involve unidirectional traffic or bidirectional traffic. When considering the higher similarity of headings in unidirectional flow and the potential for head-on conflicts in bidirectional flow, it would be expected that unidirectional traffic is preferable to bidirectional traffic. However, in heavily restricted airspaces it may be necessary to group traffic into bidirectional flows if there is a limited total volume of airspace. In this experiment the differences in air traffic flow between unidirectional and bidirectional corridors is considered by comparing the two. Figure 5.4a depicted the construction of a unidirectional corridor. Figure 5.5a shows the geometry of a similar bidirectional corridor. Again the restricted airspace boundaries are represented by red circles, the arrays of multi-color points indicate sample aircraft trajectories, the green arrows demonstrate the direction of air traffic flow and the blue rectangle indicates the study volume.

Figures 5.5b-f compare air traffic flow measures and relationships for the unidirectional corridor (blue points and curves) and the bidirectional corridor (green points and curves). When considering 5.5b, the conflict rate versus density plot, it is found that the bidirectional corridor does have a higher conflict rate than the unidirectional corridor. This trend is due to the dissimilarity of headings between aircraft moving in opposite directions versus the same direction. Figures 5.5c and 5.5d compare the average actual speed with density and the average effective speed with density, respectively. The results and trendlines show that the bidirectional corridor does see slightly lower speeds at a given density than the unidirectional corridor. Figure 5.5e shows similar declines in effective speed due to conflicts, which indicates that the slower aircraft speeds in the bidirectional corridor are primarily due to the higher conflict rate rather than greater speed loss per conflict. A similar relationship is found in figure 5.5f, which shows the fundamental diagrams for each corridor type and finds that the bidirectional corridor has a lower throughput of vehicles at higher densities relative to unidirectional corridors. The overall takeaway is that bidirectional corridors, as expected, do generate a higher conflict rate than a unidirectional corridor from the dissimilarity of headings. This higher conflict rate in turn negatively impacts vehicle speeds, throughput, and travel times. However, the degree of the differences between a bidirectional and unidirectional corridor are not large, suggesting that bidirectional corridors may be a less preferable but still manageable solution for restricted airspaces with a limited amount of accessible airspace.

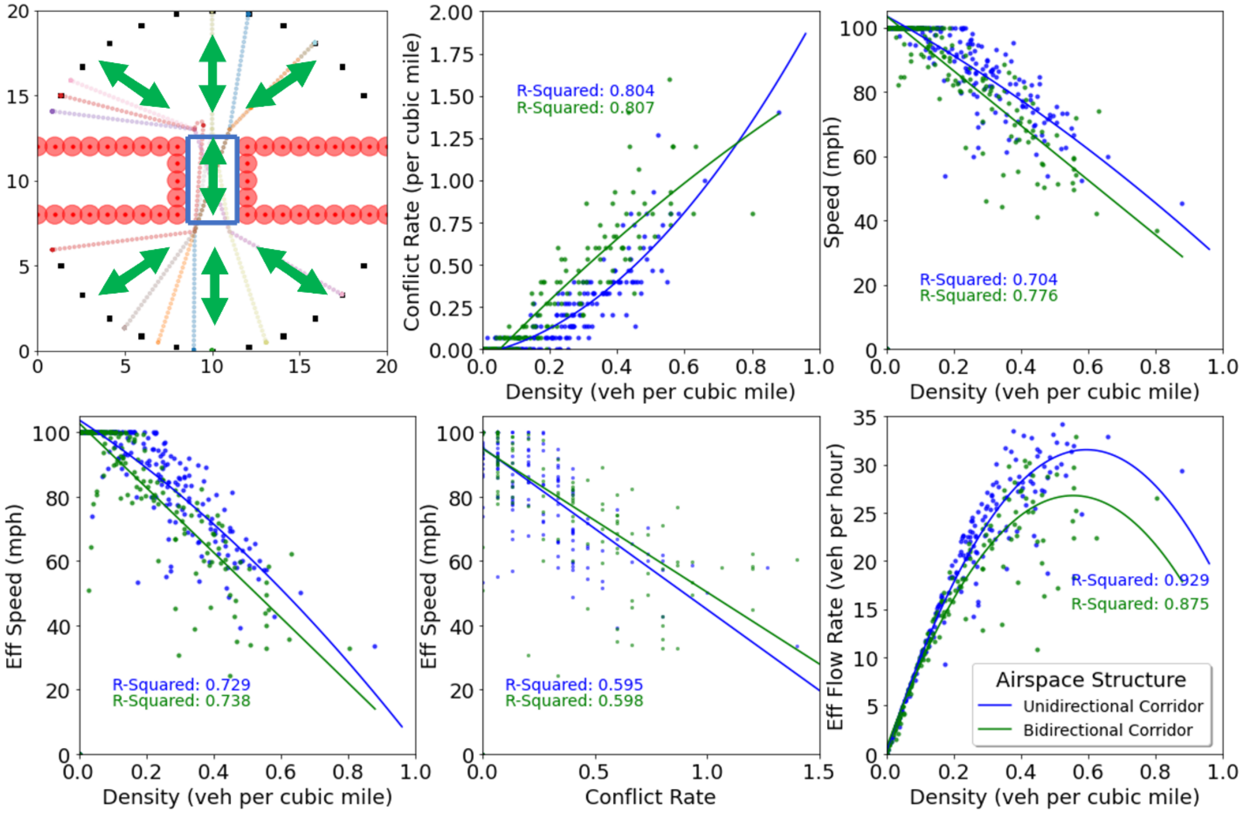


Figure 5.5 a (top left) - f (bottom right). a depicts the bidirectional corridor airspace scenario considered. b through f compare key traffic flow measures for the unidirectional corridor (blue) and bidirectional corridor (green).

The two corridor experiments so far summarized in figures 5.4 and 5.5 have studied the air traffic flow in entire corridors of airspace. What has not been examined closely are the local differences in air traffic flow within a corridor of airspace. Saberi and Mahmassani (2014) studied pedestrian traffic flows, and discovered a difference in the speed of the traffic depending on the distance from the boundary of a corridor. AAM traffic may also display similar differences in traffic flow according to the distance from a boundary. The framework for comparing air traffic flow between airspace structures highlighted in this section has been to consider the similarity of aircraft headings and the existence of restrictions that limit aircraft maneuverability during conflict resolution. Airspace immediately abutting a boundary would have less maneuverability for conflict resolution, and therefore the traffic near a boundary should see higher effective speed losses due to conflicts. However, the boundaries also serve to restrict the heading differences between aircraft near them. Restricting these heading differences would lower the conflict rate between aircraft and improve traffic flow. These two expectations combine to create a mixed effect of boundaries on air traffic flow.

To test the hypotheses a large bidirectional corridor airspace was constructed in the simulator, which is depicted in figure 5.6a. The red circles indicate the airspace restriction boundaries, and the multi-color, faded arrays of points indicate sample aircraft trajectories traveling through the corridor. The aircraft are shown to have some freedom to maneuver and dissimilar headings indicated by the variety of trajectory headings. The corridor airspace is delineated into three zones (one in the center and two near the boundaries), and the air traffic flow is measured in each zone. Figure 5.6b compares the conflict rates and density for each of the zones, with the green trendline showing that the conflict rate in the center zone actually is nearly the same as the conflict rate near the boundaries. Figures 5.6c (average actual speed vs density) and 5.6d (average effective speed vs density) compare the aircraft speeds with density, finding that air traffic in the center sees on average higher speeds than traffic near the boundaries. Figure 5.6e compares the decline in effective aircraft speeds with the conflict rate, identifying that the air traffic near boundaries does exhibit greater effective speed loss from conflicts than the center. And finally figure 5.6f creates relationships between effective flow rate and density for the three zones and finds that the maximum throughput in the center of the corridor is much higher than in the zones near the boundaries.

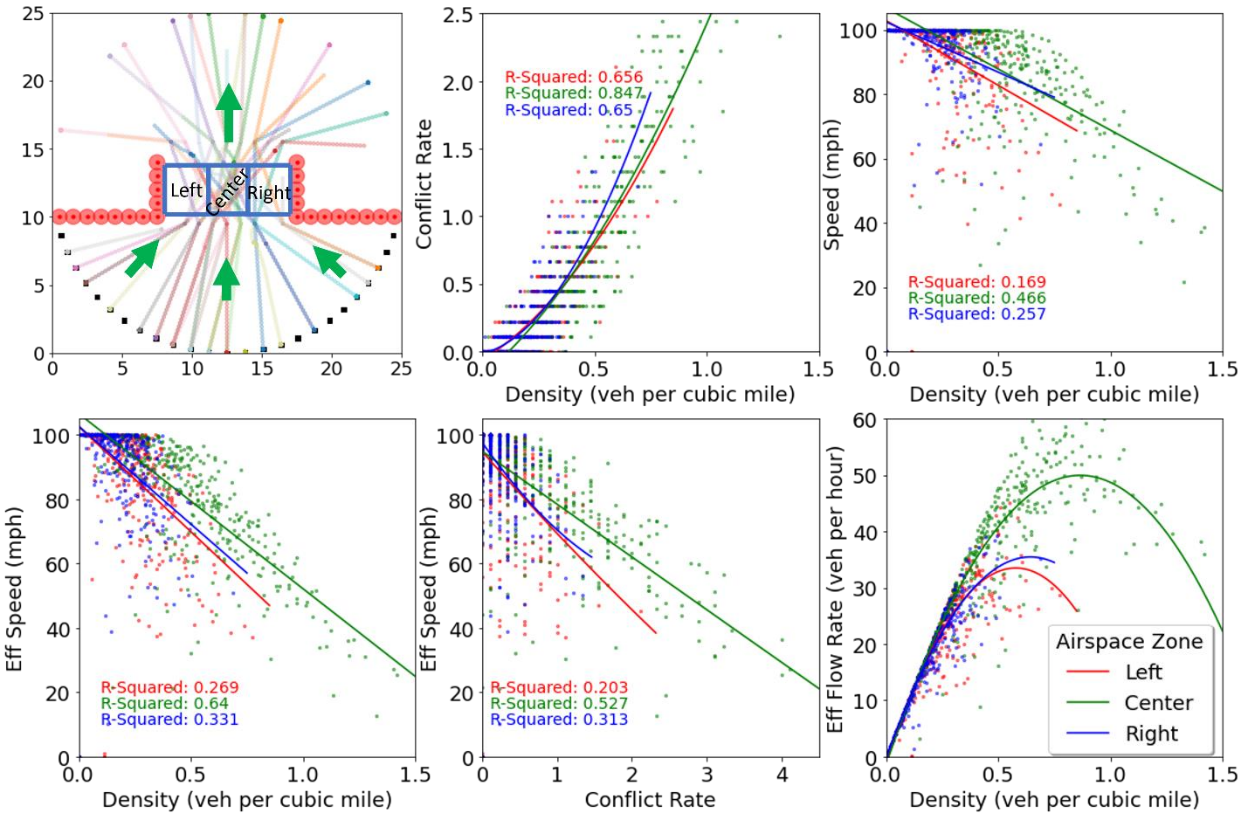


Figure 5.6 a (top left) - f (bottom right). a depicts the large bidirectional corridor airspace scenario considered. b through f compare key traffic flow measures found within three different areas of the corridor, near the left boundary (blue), in the center (green), and near the right boundary (red).

The simulated results and findings showed a mixed consistency with the hypotheses for this scenario. Rather than a higher conflict rate from density the center zone actually appears to have a similar conflict rate. It was hypothesized that the conflict rate would be lower near the boundaries because the airspace restrictions could serve to align the headings of aircraft and reduce the conflict rate. This prediction was not born out in the experiment, although this could arise from the experimental setup. Meanwhile the airspaces near the boundaries did have the higher decline of effective speed from conflicts that was hypothesized. The speeds decline faster due to conflicts near the boundaries because the boundaries serve to restrict the maneuverability of aircraft. In general the findings suggest that air traffic flow in a corridor may be improved in the center of the corridor, where higher speeds, higher effective flow rate and a higher critical density were observed from our simulated data. Such a finding could have value for AAM operators and planners, who may consider prioritizing routing in the center of corridors to improve the travel times and throughput of vehicles using the corridor.

This section has used three different comparisons of structured airspace scenarios to explore how air traffic flow behaves within a restricted corridor. The broad findings have suggested that corridors experience the same air traffic flow patterns as other unstructured airspaces. However, the study of corridors also indicated a framework for thinking about restricted airspaces. When evaluating a restricted airspace the similarity of aircraft headings and the maneuverability of aircraft for conflict resolution should be considered, as these directly impact the conflict rate and effective speed reductions from conflicts which are key components of determining air traffic flow. The results also found that corridors do have lower conflict rates relative to unstructured airspace, with unidirectional corridors generating fewer conflicts than bidirectional corridors. This did not necessarily mean improved traffic flow in corridors however, since figure 5.4 found that corridors could have higher effective speed reductions from conflicts relative to unstructured airspace. This is because of the difficulty in aircraft maneuvers to resolve conflicts in a restricted airspace. The traffic flow in unidirectional corridors was found to be better than bidirectional corridors (higher vehicle speeds and throughput), although this difference was not large, suggesting that bidirectional corridors could still serve as an effective airspace structure. And the scenario studying local differences in air traffic flow suggested that the center of a corridor may generate faster vehicle speeds and improved traffic throughput, making it more attractive for vehicle routing than airspaces near the boundaries.

5.3 Air Traffic Flow through Corridor Transitions (Bottlenecks)

Transitions between airspaces occur when airspaces are not uniform within a network. In a network of corridors transitions may occur when corridor widths vary, the airspace structure varies, or unstructured airspaces meet structured airspaces. These transitions are known problems for traffic flow, often forming bottlenecks. It would be possible to construct a network of corridors without such transitions or bottlenecks by avoiding varying corridor sizes or other similar transitions. However, varied airspace structures allow for locally customized structures that could improve different traffic flow measures such as travel times and capacity, and to allow for varied airspace structures transitions between those airspaces are necessary.

The goal of this experiment is similar to the experiment in figure 5.6: to explore localized traffic flow differences in airspaces near a transition. A simple, unidirectional corridor transition scenario was constructed, simulated, and measured to better understand the movement of air traffic flow through such transitions. The scenario constructed (see figure 5.7a) considers a transition between an unstructured airspace and a corridor. This scenario will obviously create a bottleneck, because it condenses traffic flow scattered over a wide airspace into a much smaller, restricted airspace. The condensed airspace will have a higher density, which in turn will increase the conflict rate, reduce the aircraft speeds and impact the throughput.

The local air traffic flow near the transition is measured in five zones, which are represented by the blue squares in figure 5.7a. These zones are grouped into three categories: ends, sides, and the middle. The ends are zones near the transition but are not adjacent to the corridor due to restricted airspaces. Aircraft passing through the “ends” zones must also pass through another measured zone to enter the corridor. The sides are zones that are adjacent to the restricted sides of the corridor. The middle is defined as the zone that is adjacent to the center of the corridor which is not impacted by restrictions adjacent to it. The red circles in figure 5.7a depict the boundaries of the airspace restrictions, while the green arrows demonstrate the direction of traffic flow. The arrays of multi-colored points show sample trajectories of aircraft moving through the system.

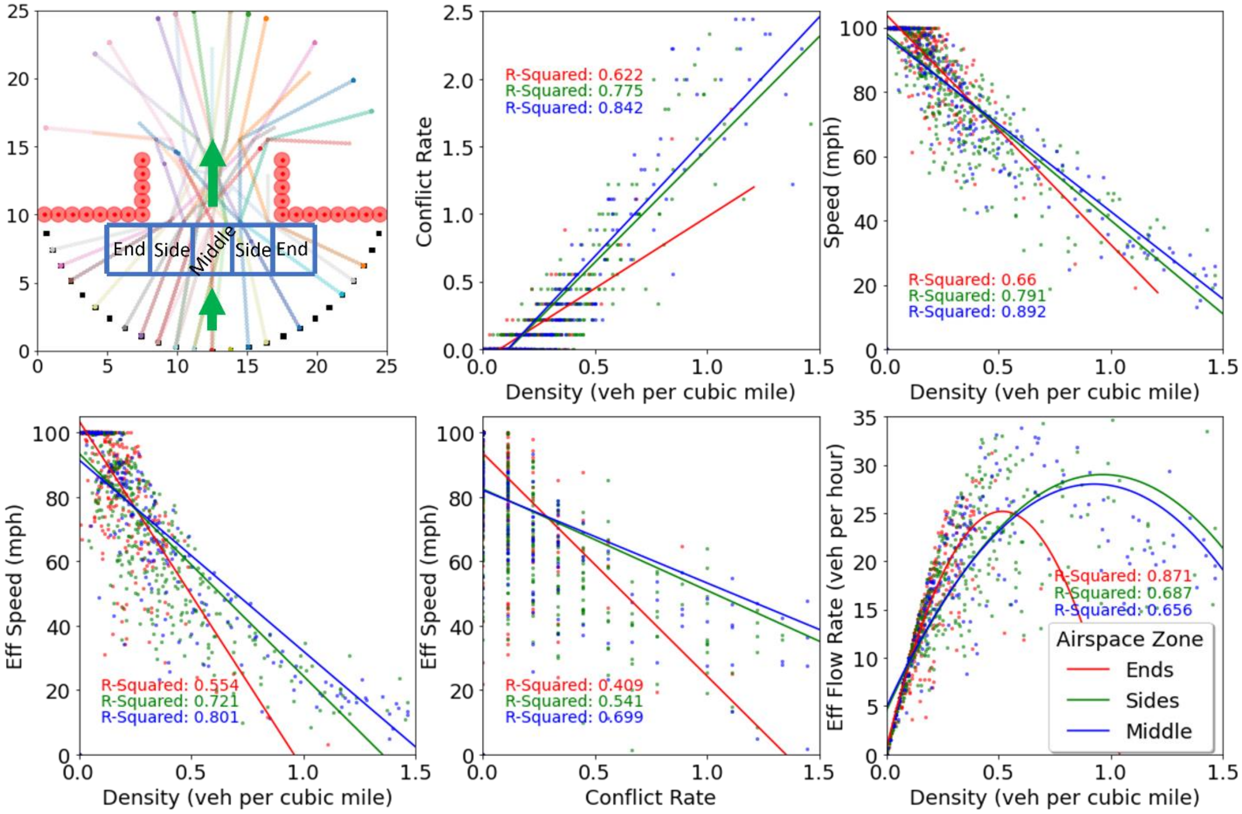


Figure 5.7 a (top left) - f (bottom right). a depicts the transition between unstructured airspace and a corridor considered. b through f compare key traffic flow measures found within the different zones of airspace near the bottleneck.

Figure 5.7b depicts the conflict rates in each group of zones based upon the density of aircraft. The conflict rates in each zone are similar, with the conflict rate in the ends measured to be somewhat lower than in the sides and middle, which are both directly adjacent to the corridor.

Figures 5.7c and 5.7d show the average speed and average effective speed of aircraft in the zones relative to density. The sides and middle again demonstrate very similar patterns of speed reductions due to density. The ends however see a faster decline in the average speeds, indicating slower traffic at density and longer travel times. A reason for this is found in figure 5.7e, which shows that the effective speed in the ends decreases more quickly due to the conflict rate than in the sides or the middle. The result is that the traffic flow in the ends has a somewhat lower maximum effective flow rate and a lower critical density, which is found in figure 5.7f.

The findings from this experiment are centered around the higher effective speed loss due to conflicts in the ends zones when compared with the zones directly adjacent to the corridors. The ends zones are the only measured zones adjacent to restricted airspace, supporting a conclusion from section 5.2: that air traffic flows near boundaries and restrictions suffer from the loss of aircraft maneuverability in the form of longer detours and delays from conflict resolution. The consequence for this transition experiment is that the ends zones ultimately experience worse traffic flow in the form of slower speeds and a lower critical density. When designing or planning for transition airspaces AAM planners should look for ways to lessen the impact of congestion in the bottleneck, but should also be mindful of maintain maneuverability for aircraft in the event of conflict resolution.

5.4 Air Traffic Flow in Corridor Intersections

While corridors may form the majority of a network of restricted airspaces, there are other forms of airspace structures to consider and study the traffic flow within. The merging, diverging, or crossover of traffic between two corridors would create an intersection, and depending on the form of intersection would change the air traffic flow. Intersections are known points of conflict for traffic flow in all modes, largely due to the presence of multiple traffic flows with different headings. The differences in headings between aircraft have been shown in section 4.6 to generate conflicts as vehicles cross in front of each other. Therefore, intersections of restricted corridors are key airspace structures to study and understand the traffic flow within. Two experiments with intersections were conducted in this work: a four-way bidirectional intersection and a four-way unidirectional intersection.

Using the insights from section 5.3, an intersection can be thought about in terms of the conflict rate due to the similarity of headings, and the effective speed loss from conflicts that result in detours or delays of aircraft. When compared with the previously tested corridor airspaces, intersections have less similar headings since they involve conflicting traffic flows from different directions. Therefore, intersections should in general have higher conflict rates than corridors without intersections. Intersections also have similarly restricted maneuverability of aircraft as corridors, indicating similar speed losses from conflicts.

In the first experiment, the traffic flow in a four-corridor, bidirectional intersection is measured and compared with traffic flow in a typical bidirectional corridor (without an intersection). Figure 5.8a represents the setup of this intersection, with red circles representing the boundaries of the restricted airspace, the arrays of multicolored points showing sample aircraft trajectories through the intersection, the green arrows indicating the directions of traffic, and the blue square delineating the study volume. In figure 5.8a it is important to note that aircraft can originate in any of the four corridors and is destined for any other corridor by moving through the intersection. In figures 5.8b-f the aggregate traffic flow measures are represented for the intersection (in blue) and compared with traffic flow in a bidirectional corridor (in green). Figure 5.8b plots the conflict rate compared with density. As hypothesized, the conflict rate in the intersection is higher at all densities relative to the conflict rate in a corridor without intersecting traffic flows. In figures 5.8c, d, and f, the average actual speed, effective speed, and throughput declines much more quickly in an intersection at density relative to a corridor without an intersection. These findings demonstrate poor traffic flow conditions overall relative to a corridor at the same density. The results shown in figure 5.8e, the effective speed versus conflict rate, show that the effective speed losses from conflicts in an intersection are slightly worse than in a corridor. The loss of effective speed from conflicts is due to detours and delays, which may be worse for conflicting traffic flows with dissimilar headings than for aircraft traveling in a similar direction. Overall the four-corridor intersection demonstrates significantly worse traffic flow at both low and high densities relative to corridors. The intersection demonstrates a high conflict rate from the conflicting directions of the traffic flows, and the high number of conflicts is the primary driver behind the deteriorating aircraft speeds and throughput. This finding indicates an area of concern for AAM planners and operators: that intersections between corridors may generate significant breakdowns in traffic flow and raise travel times and lower throughputs in the system. Thus planners should strive to create systems that avoid intersections of aircraft that will create conflicting traffic flows.

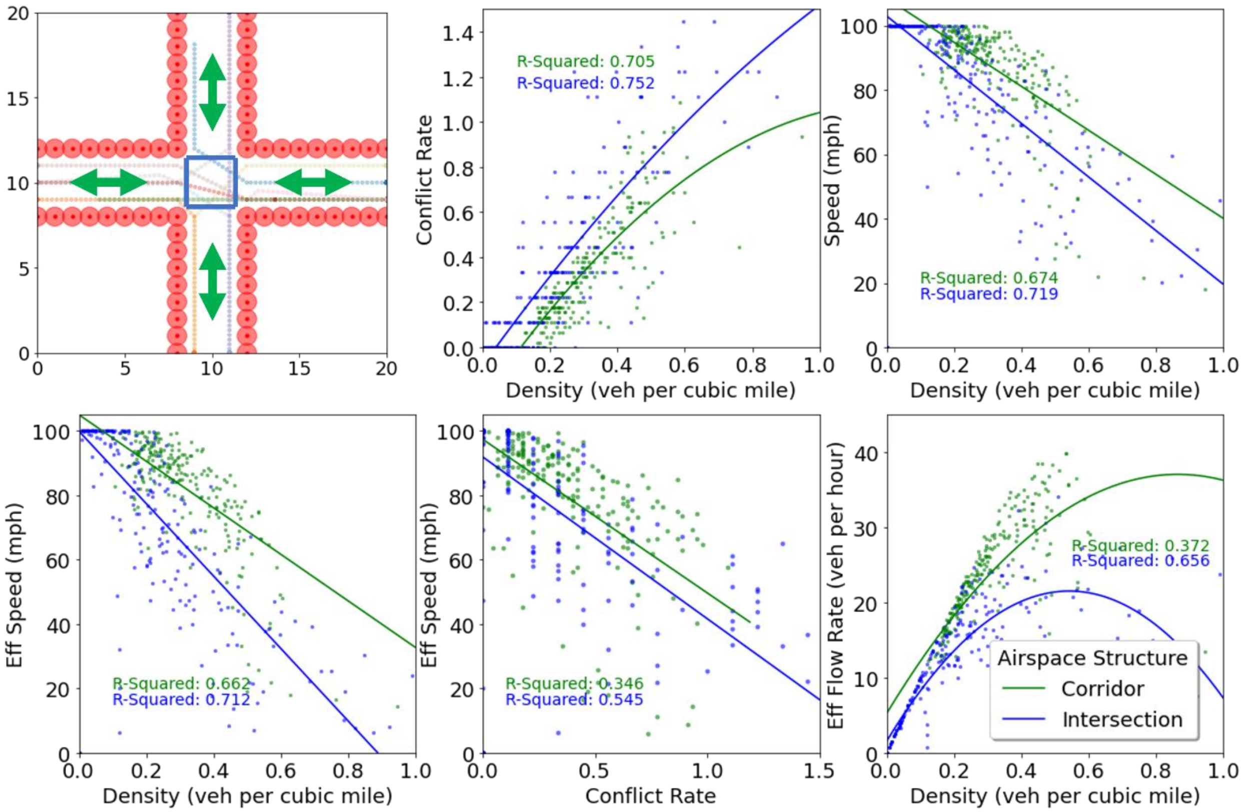


Figure 5.8 a (top left) - f (bottom right). a depicts the four-corridor, bidirectional intersection scenario considered. b through f compare key traffic flow measures found within the intersection (blue) to a bidirectional corridor without an intersection (green).

The second intersection experiment performed tested the impact of a four-way intersection utilizing unidirectional corridors compared with bidirectional corridors. In section 5.2 unidirectional corridors were found to create slightly improved traffic flow conditions when compared with bidirectional corridors. This effect was due to a slightly lower conflict rate which came from similar aircraft headings. In the experiment with unidirectional corridors forming an intersection the same groups of airspace restrictions and geometry of the scenario as the bidirectional intersection were used. This geometry is shown in figure 5.9a, where the red circles indicate the restricted airspace boundaries. The key difference in the unidirectional intersection scenario is that rather than originating on any of the four sides, all aircraft move from the left or bottom sides through the intersection in the middle to the right or top sides. The green arrows depict the directions of movement. Sample trajectories of aircraft are shown as arrays of multi-colored points, and the study volume is represented by the blue square in the intersection.

Similar to the comparison of unidirectional and bidirectional corridors in section 5.2, the conflict rate in the unidirectional intersection is slightly lower than for the bidirectional intersection (shown in figure 5.9b). Again this is likely due to the similarity of aircraft headings, which is improved in this intersection by reducing the number of directions that aircraft come from. The other key determinant of air traffic flow differences is the effective speed loss from conflicts, which figure 5.9e shows that the rate of effective speed loss from conflicts is much faster in a bidirectional corridor than a unidirectional corridor. Section 5.2 noted that restrictions creating less aircraft maneuverability could cause greater effective speed loss from conflicts, but given that the unidirectional and bidirectional corridors share the same restriction geometry that does not apply in this experiment. The comparison of a bidirectional intersection to a bidirectional corridor (figure 5.8) noted that the effective speed loss was slightly worse in the intersection than the corridor, which may have arisen from the dissimilarity of aircraft headings creating longer detours and delays in the intersection compared with the corridor. The results in figure 5.9e support that suggestion, because the unidirectional intersection with similar aircraft headings suffers less effective speed loss from conflicts than the same intersection in a bidirectional setup with dissimilar aircraft headings. Based upon the lower rate of effective speed loss, the average aircraft speeds and effective flow rate at density is significantly higher for the unidirectional corridor than the bidirectional corridor (figures 5.9c,d,f).

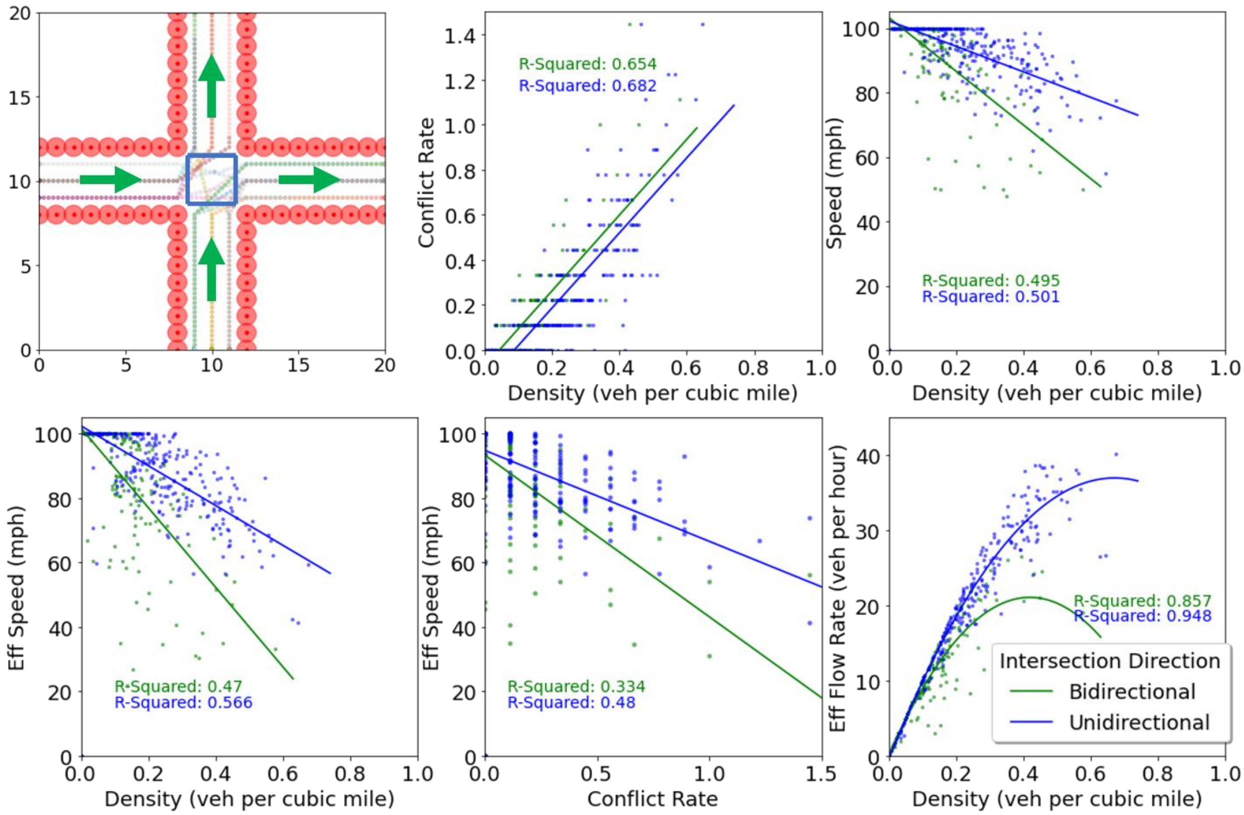


Figure 5.9 a (top left) - f (bottom right). a depicts the four-corridor, unidirectional intersection scenario considered. b through f compare key traffic flow measures found within the unidirectional intersection (blue) to a bidirectional intersection (green).

These findings indicate first that unidirectional intersections demonstrate improved traffic flow relative to bidirectional intersections. The results shown in figure 5.8 demonstrated that intersections in corridors could suffer significant traffic congestion problems at higher densities and were potential bottlenecks in the network. However, the findings in figure 5.9 showed that an effective improvement would be to use unidirectional intersections of corridors instead. In section 5.2 it was proposed that while bidirectional corridors had slightly worse traffic flow than unidirectional corridors, they could still be effective if needed due to spatial constraints. The findings in this section extend that to indicate that the traffic flow in bidirectional intersections may be significantly worse than unidirectional intersections. Therefore, if it were necessary to use bidirectional corridors in a network, it would be desirable to avoid using bidirectional intersections, and instead design a network that could do without intersections or utilize unidirectional intersections instead.

Secondly, the similarity of aircraft headings also plays a role within the rate of effective speed loss per conflict, rather than only the conflict rate. Dissimilar aircraft headings can cause longer detours and delays to resolve, causing greater reductions in effective speed from conflicts. The result for intersections is that the conflicting traffic flows can slower average speeds with a lower conflict rate than would be seen in corridors without intersections. It is also true that the dissimilarity of headings in an intersection creates a higher conflict rate. With both a higher conflict rate and a greater effective speed loss per conflict it becomes important for conflicts in intersections to be managed and resolved efficiently to mitigate and reduce traffic congestion.

5.5 Air Traffic Flow in Unstructured Airspaces with Sporadic Restrictions

Some airspace restrictions do not attempt to structure air traffic flows or deny large sections of airspace like corridors do. Instead these restrictions exist only to keep aircraft out of a small restricted airspace within a broader area of unrestricted airspace. Airspaces near vertiports may be restricted to keep out aircraft not on approach or take-off, or flight restrictions may exist around an obstacle or area on the ground. If these restrictions exist within a system of unstructured airspace they do not resemble a method for organizing air traffic flows, and are essentially different from corridors.

There are a few key questions regarding these kinds of sporadic restrictions within an unstructured airspace. These research questions are: 1) do sporadic restrictions significantly impact air traffic flow? 2) Will these restrictions impact the maneuverability of aircraft in conflict resolution, increasing the rate effective speed loss from conflicts? And 3) what impact on the conflict rate would sporadic restrictions have?

In order to answer these questions an experiment was constructed in which separated, circular airspace restrictions representing vertiports were placed within an otherwise unstructured airspace. A depiction of the setup is shown in figure 5.10a, with the airspace restrictions (or vertiports) represented by red circles. The vertiports are arranged in a grid, and multiple levels of restricted densities were tested, ranging from 24% of the airspace is restricted by 36 vertiports, down to 0% of the airspace is restricted, creating a completely unstructured airspace. Aircraft originate along the edges of a circle and move to a random other point on the circle, such that the headings of aircraft moving through the airspace are random. The directions of aircraft movement are represented in figure 5.10a by the green arrows. Sample trajectories of vehicles are shown by the arrays of multi-colored points. The blue square shows the zone in which the air traffic flow was measured.

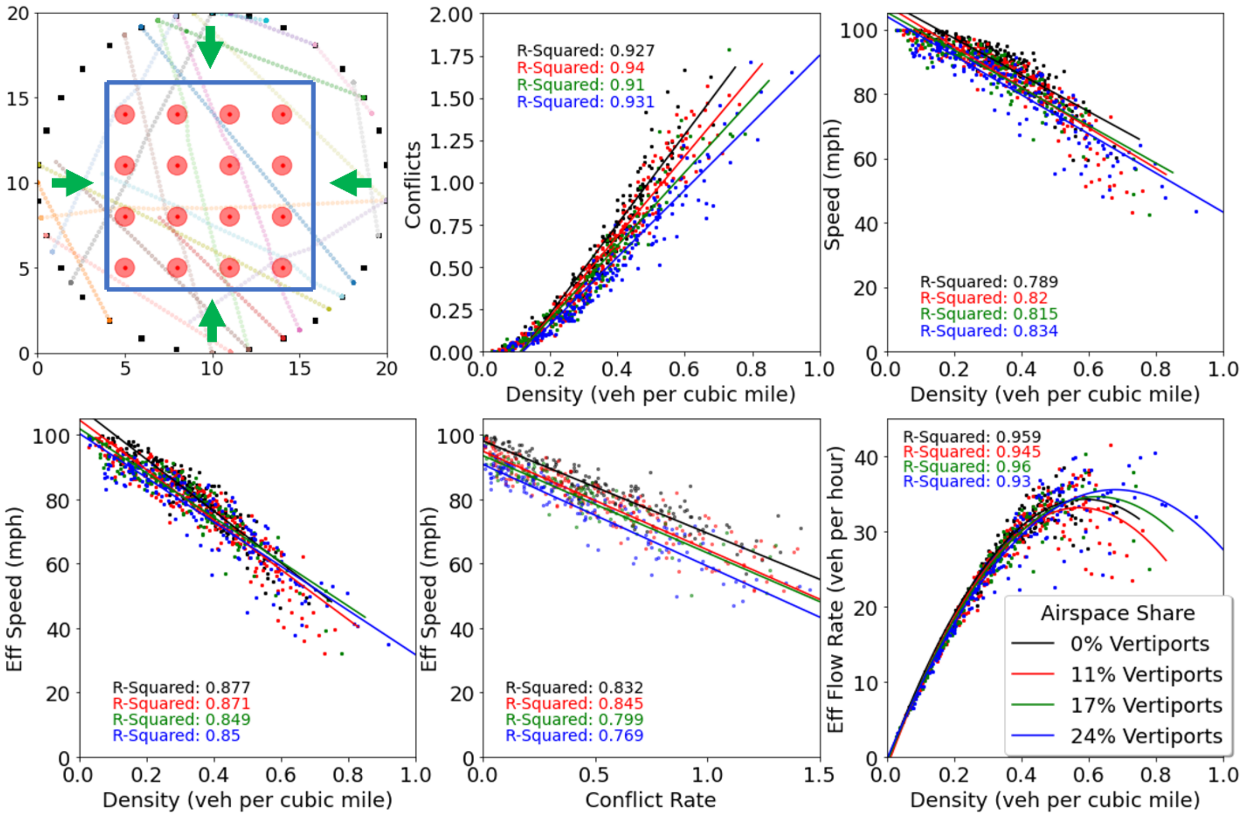


Figure 5.10 a (top left) - f (bottom right). a depicts as an example the sporadic placement of vertiport restrictions within an unstructured airspace for the 11% vertiports scenario. b through f compare key traffic flow measures found within the unstructured airspace when considered with varying numbers of airspace restrictions (vertiports).

In regards to the first research question, if sporadic restrictions significantly impact air traffic flow, the answer appears to be that they do not, at least when controlling for vehicle density (as the traffic flow measures do) and up to the number of restrictions tested. Figures 5.10c and 5.10d depict the average vehicle speeds at density for each level, and the speeds of aircraft remain quite similar across all densities for each level. Furthermore, when comparing the effective flow rates at density figure 5.10f shows that again the traffic flows appear very similar, with tightly grouped maximum throughputs and critical densities. It is important to remember though that airspace restrictions cannot be added ad nauseum with no impact on traffic flow.

Rather more airspace restrictions will decrease the amount of available airspace which will increase vehicle densities, and increasing densities will lower vehicle speeds and impact traffic flow.

Given the findings of the first question, when it comes to the second and third questions it might be expected that there are no notable differences to answer with. But that may not be telling the whole story. The second question asked if the rate of effective speed loss from conflicts would differ due to sporadic restrictions. Figure 5.10e depicts this relationship, in which the 0% vertiports scenario has the highest average effective speeds from all conflict rates, while the higher levels of vertiports result in lower average effective speeds. While the differences are slight, this result may support the findings from sections 5.2 and 5.3, that airspace restrictions result in greater effective speed losses from conflicts due to a loss of maneuverability near restrictions during conflict resolution.

The third question wondered if sporadic airspace restrictions impacted the conflict rate of aircraft. Again here the differences appear slight, but in figure 5.10b the conflict rate from density is notably lower with more sporadic vertiport restrictions. Previous results found that when considering airspace restrictions the alignment of headings can create differences in the conflict rate. The same concept appears to apply here, although in a more subdued way. The establishment of the airspace restrictions, especially in a grid, appears to create its own system of poorly delineated corridors within the unstructured airspace. The aircraft, while avoiding the restrictions, concentrate within these available corridors. At higher numbers of restrictions these corridors may become better defined, further reinforcing the alignment of headings and ultimately decreasing the conflict rate.

The experiments with sporadic restrictions in an unstructured airspace ultimately found that such restrictions did not create significant traffic flow differences. This finding is notable because it would indicate that some amount of separated restrictions could be implemented in an unstructured system with only minor effects on the system throughput or travel times. Unnecessary restrictions are still inadvisable however, since each restriction does decrease the amount of available airspace and increase densities of aircraft. The findings may also point to the development of the impact of airspace restrictions on air traffic flow. Airspace restrictions will align aircraft headings within the available airspace and increase detours and delays from conflicts due to a loss of maneuverability. Each of these effects was found to be minor at a low density of restrictions, but as the number of restrictions increases the effect appears to become more pronounced. Ultimately these effects at a high number of restrictions could approximate the effects within restricted corridors, which also operate at a high share of restricted airspace. The findings thus suggest that these two effects are not found only within corridors or similar airspace structures, but will occur in some form across all kinds of restricted airspaces.

5.6 Discussion of Airspace Restrictions on Air Traffic Flow and Conclusion

This chapter has studied the local impacts of airspace restrictions on air traffic flow. Airspace restrictions such as corridors are likely to comprise the majority of a UAM service network during the early and intermediate execution of services. Restricted airspaces may also continue to play a large role in the network in an advanced state of UAM services because they are useful for both structuring air traffic flows and safely separating air traffic from obstacles or sensitive areas.

In order to study restricted air traffic flow a series of experiments were conducted within a simulation of restricted airspaces. The air traffic flow in these airspace structures was measured and patterns between measures studied and compared. When measuring traffic flow within a restricted airspace, it is important to measure the vehicles within the proper study volume. Including extraneous or restricted zones of airspace within the analysis can distort the traffic measurements and affect the results. Restricted zones of airspace should always be excluded from measures of traffic flow, and the precise zone of airspace studied should be considered to not capture flows of traffic in unrelated areas.

There are three important findings for the impact of airspace restrictions on air traffic flow. These three findings and their developing impacts on air traffic flow are represented by the flow chart in figure 5.11. The first is that additional restricted airspaces can create higher densities of aircraft within the available airspace. By restricting airspace the amount of available airspace decreases, raising the density of aircraft by shifting the trajectories of the same number of aircraft into a smaller airspace. The framework of air traffic flow in section 4.1 stated that higher aircraft densities increases the conflict rate, in turn reducing the average vehicle speeds. These concepts were observed in every experiment with traffic flow in a restricted airspace. In every case higher densities created more conflicts, reduced vehicle speeds (thereby raising travel times), and impacted the throughput. While the impacts of airspace restrictions on traffic flow can vary, the large impact of density on traffic flow is ubiquitous to all restrictions and AAM planners and operators should design airspace structures that do not unnecessarily restrict the total amount of available airspace and raise aircraft densities.

The second broad finding is that airspace restrictions can also impact the effect of conflicts on the effective speed of aircraft. Restrictions reduce available space for conflict resolution, which decreases the maneuverability of aircraft and can cause longer detours and delays due to conflicts, lowering the average effective speed. Lower average effective speeds are important for UAM service because they directly translate to slower travel times, worsening the level of service and efficiency of the operation. This effect was found in airspaces adjacent to restricted boundaries (figures 5.6 and 5.7). This negative impact from restricted airspaces should be considered in planning when structuring airspaces and during operations when routing aircraft. Aircraft trajectories might favor the centers of corridors or zones of airspace not adjacent to restrictions which can support a higher throughput.

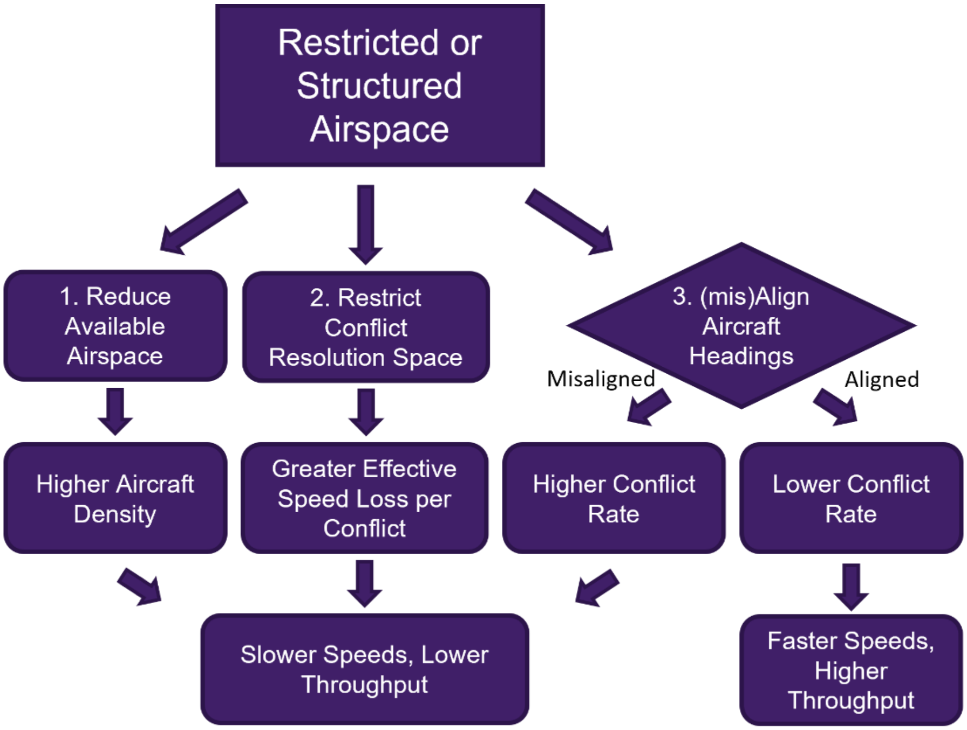


Figure 5.11. Impacts of restricted or structured airspaces on the development of air traffic flow.

The third overall finding is that airspace restrictions may align (or misalign in the case of intersections) aircraft headings, which will impact the conflict rate. Corridors will generally align the aircraft headings by restricting the directions from which aircraft can move through the airspace. A greater alignment of headings will reduce the conflict rate, which was first found in chapter 4. The reduced conflict rate which will improve traffic flow conditions by requiring fewer detours and delays from conflict resolution. Structures creating a greater similarity of headings will benefit the most, which was found in the comparison of unidirectional corridors and unstructured airspace (figure 5.4), unidirectional and bidirectional corridors (figure 5.5), and unidirectional and bidirectional intersections (figure 5.9). Even sporadic vertiport restrictions at higher densities had the effect of creating de-facto corridors of airspace that aligned headings and reduced conflict rate (figure 5.10). When considering how air traffic flow will behave within a structured airspace the alignment of aircraft trajectories must be considered.

These three criteria form a basis on which restricted and structured airspaces can be evaluated. They also represent a mixture of effects to consider. For example, corridors do organize aircraft headings and reduce conflict rates, although traffic near the restrictions sees greater effective speed losses from conflicts. Corridors might also unnecessarily shift different trajectories into the same airspace, creating a higher density and impacting the speeds of vehicles.

Another form of airspace structure is the assignment of air traffic into altitude layers. By assigning aircraft to different altitude layers sufficiently separated from each other and restricting movement between altitudes, it is possible to organize the air traffic flow. The separation of air traffic into altitude layers alone with no other organization will do nothing except spread the density of aircraft out over more vertical airspace. However, by combining altitude layers with some structure for restricting aircraft headings, it is possible to reduce the conflict rate and increase the throughput of aircraft. The geo-vectors concept detailed by Hoekstra et al. (2018) layers airspace into altitudes of aircraft with similar headings, with the result that the conflict rate is lowered. Similarly, a network of corridors with intersections might layer the intersections in order to vertically separate conflicting traffic flows, thereby reducing the conflict rate. This application of layering then has the benefits of additional organization of airspace similar to corridors, without necessitating the creation of new structures on the same altitude levels.

There were several limitations to the work in this chapter. Perhaps the broadest limitation was the heavily context-dependent nature of airspace restrictions. Airspace restrictions and structures can vary widely based upon their geometry, and these variations do affect the trajectories and headings of aircraft, impacting the traffic flow. Because this makes each geometry unique, it is impossible to establish mathematical models that apply to all shapes and forms of airspace structures. Instead this chapter established only broad trends that apply to air traffic flow in restricted airspaces, and based upon those trends developed a framework of considerations for evaluating restricted air traffic flow. There were also a number of limitations to the setups of experiments, which only studied traffic flow in broad zones of airspace for simplified airspace structures. By using a limited variation in studied zones in several experiments the results may suffer from an increased granularity.

Future work could delve deeper into the framework established here surrounding the local impacts of airspace restrictions. Specifically the work on what affects the loss of effective speed from conflicts could be extended. Perhaps a study of conflict resolution at the individual level could better illuminate the transition from a single conflict with a set of parameters such as heading, spacing requirement, and nearby restrictions to a resolution with a detour or delay. Ultimately these detours and delays accumulate to impact the average effective speed of the traffic flow. There could also be an extension of the framework developed here to look at the intersections of corridors more closely, and explore how the angle of the intersecting flows and the presence or lack of restrictions and separation within the intersection affects the intersection.

The next chapter, chapter 6 will take a network-level view of the impact of airspace restrictions. It will study different structures of airspace across the entire system. Restricted airspaces can align trajectories and lower conflict rates, but may also increase flight distances, elongate travel times and lower the system capacity. These trade-offs and others will be measured and examined. After that a method for managing air traffic flow in a network of airspace through subdivisions of airspace with traffic flow measurement will be proposed and studied.

Chapter 6

The experiments conducted in chapter 5 studied local air traffic flow in restricted airspaces and the effects of restrictions on traffic behavior. Several airspace structures were considered, including corridors, intersections, bottlenecks, and sporadic restrictions. The results from these experiments suggested a framework for thinking about the traffic flow impacts of airspace restrictions. Airspace restrictions affect local traffic flow in three main ways: by concentrating the traffic flow, aligning (or misaligning) aircraft headings to lower (or raise) the conflict rate, and by restricting the available conflict resolution space. While each of these concepts was shown to affect the traffic flow developed at the local level, they do not describe the network level implications of airspace structures and restrictions. For example, the effects of corridors on local traffic flow were studied and discussed, but the strategic impacts of a network comprised of corridors warrant further study. These strategic impacts from structuring airspace with restrictions will be studied in this chapter at the network level.

Airspace structures and restrictions are necessary parts of any system of airspace in order to separate aircraft from obstacles, sensitive areas, and each other. Some airspace restrictions, like flight restrictions near buildings or other ground obstacles, are strictly for safety purposes. However, airspace restrictions can also be used for other purposes, such as reducing noise in a residential area or to structure and improve air traffic flow. Airspace restrictions can create structures such as corridors, bottlenecks, and intersections. These structures contain air traffic and separate it from the restricted areas, but they also form the building blocks of an UAM network of airspace. Such a network of airspace includes and is affected by these structures. The goal of chapter 6 is to study and identify broad, network-level impacts of airspace structures and restrictions.

In this work the broad impacts of a network consisting of these airspace structures are explored through comparisons of different forms of restricted and unrestricted airspace networks. In chapter 5 it was mentioned that the effects of structured airspaces can be very context dependent according to factors such as the airspace geometry. It would be impossible to predict and consider all possible forms of airspace structures, as it is impossible to predict and consider all possible airspace networks. Instead this work focuses on developing several relatively simple airspace network concepts that can be tested and compared easily. From these simple networks the findings can then be applied more broadly to potential real world networks. Four networks are constructed and results for the networks simulated. The networks are then compared across seven key performance metrics that could represent various network goals of safety, efficiency and equity of externalities. The findings and discussion examine the trade-offs that emerge between network architectures in the performance metrics.

The networks considered in this chapter will generate interesting insights that can be applied more broadly to many airspace networks and network shapes. The results and insights from this chapter can help UAM planners and operators to devise airspace networks that are best suited to their specific locations and demands. For example, the findings suggest that highly restricted corridors may be most effective relative to other network architectures for very high demand locations. For lower demand locations however less restrictive network architectures are generally more efficient. The discussion of the findings can inform future research and planning for UAM network architectures.

6.1 Network Shapes

Airspace network architecture can vary greatly. Completely unstructured airspaces could allow aircraft to fly in any direction, through any airspace, at any altitude. On the opposite end of the spectrum, restrictive fixed-route corridors require aircraft to follow a predefined path, allowing for no navigational freedom. There are many different measures in between that could partially structure or restrict the airspace, such as creating defined altitude levels of airspace, restricting the headings of aircraft within specific zones, establishing keep-out flight restrictions, or forming corridors of available airspace for aircraft to use. The work in this chapter focuses on using four simple types of airspace networks that can illustrate key insights about airspace networks. These four networks are described in this section.

Unstructured Network

The first network considered is an “unstructured” network. This form of network attempts to emulate a network with very little structure governing the aircraft, maximizing navigational freedom. Aircraft in this network face no airspace restrictions. Because of this aircraft have a very high degree of navigational freedom, which allows aircraft to route on the shortest possible path between their origin and destination. While aircraft are allowed to fly at any altitude, aircraft are initially assigned to one of four altitudes randomly and may deviate from this altitude during conflict resolution. Vertiports in this network are organized in a grid pattern, with aircraft departing and arriving from any vertiport, determined by a uniform random distribution (so long as the origin and destination are different). There are no airspace restrictions near vertiports for aircraft passing by. Starting trip times for aircraft are assigned according to a normal distribution to emulate a peak period of traffic flow. The traffic flow in the network is measured across the entire network and range of altitudes. Each traffic flow measure is taken using the previously described measures (see chapter 3), while other key network metrics are described in section 6.2.

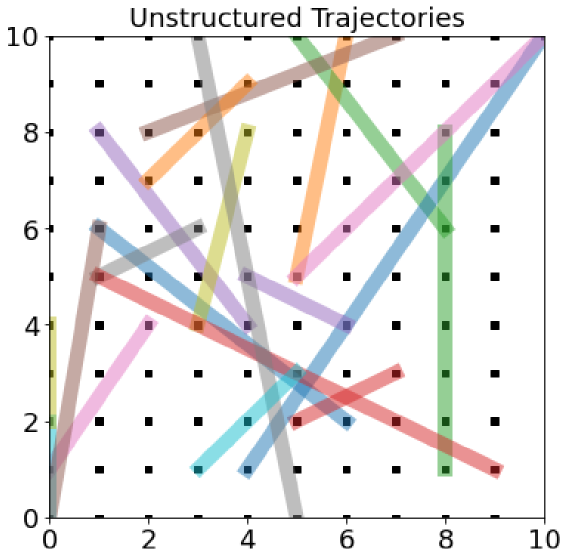


Figure 6.1. Top down view of the unstructured network in the simulations. The colored lines represent aircraft trajectories, and the black squares mark the locations of vertiports.

Geo-vectored Network

A geo-vectored network is the second network, which is similarly unrestrictive. This network makes use of the “geo-vectored” concept introduced by Hoekstra et al. (2018) and studied in this dissertation initially in section 4.5. Geo-vectors in this context refers to a series of pre-defined altitude levels that aircraft fly at, with each level restricting the headings of aircraft. The effect is that aircraft with similar directions are grouped together by altitude. In the network constructed here aircraft are organized into 4 different altitude levels, with each having a heading range of 90 degrees. There are no keep-out restrictions, allowing aircraft a high degree of navigational freedom and the ability to route directly to their destination. Vertiports are organized in a grid system without restrictions near the vertiport. Aircraft are assigned an origin and destination vertiport by uniform random distribution (again as long as the origin and destination are not the same). Aircraft take-off times are assigned by a normal distribution. A study volume encompassing the entire network and all 4 altitude levels measures the traffic flow and key network metrics of aircraft within it.

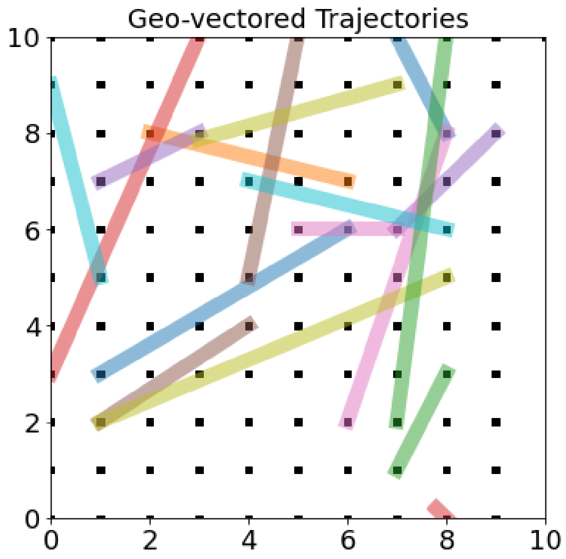


Figure 6.2. Top down view of the geo-vectored network in the simulations. The colored lines represent aircraft trajectories, and the black squares mark the locations of vertiports.

Free Route Corridors Network

There are two network setups representing restrictive airspace networks, the first of which is comprised of free route corridors. In this setup smaller unstructured regions of airspace are connected by unidirectional corridors, with free routing in corridors. Aircraft are restricted to keep within the unstructured regions of airspace or corridors, but otherwise may follow the shortest possible path utilizing the available airspace. There are two different altitude levels for the airspace, allowing for the separation of aircraft by direction in the corridors. Vertiports are grouped into five distinct unstructured regions around the network, with regions at each corner of a square network and a fifth in the middle. Corridors connect each region with the others, except for regions at opposite corners, which are connected by the other corridors. Aircraft are assigned to an origin in one region (chosen by random distribution) and a destination in any other region. Trip starting times are again assigned by normal distribution to simulate a period of peak traffic, with rising and falling demand. The traffic flow measures and key network metrics are calculated in a study volume that encompasses both altitude levels are the entire network of unstructured regions and corridors, minus the restricted airspaces between regions and corridors.

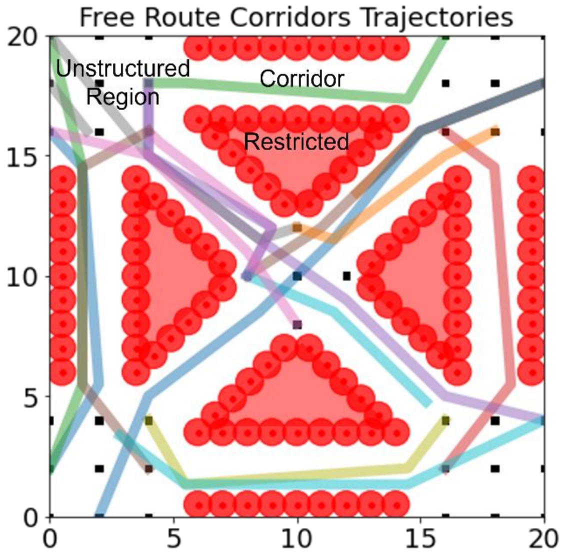


Figure 6.3. Top down view of the free route corridors network in the simulations. The colored lines represent aircraft trajectories, and the black squares mark the locations of vertiports.

Fixed Route Corridors Network

The most restrictive network considered is for fixed route corridors, or a network of vertiports connected only by fixed paths for aircraft through otherwise restricted airspace. The construction of this network is a grid of vertiports and unidirectional links, with two altitude levels, one for each direction along the link. In this network vertiports also operate as intersections for corridors. Aircraft may ascend or descend to a new altitude level at any vertiport. The fixed paths are considered as narrow and only allow a single aircraft at each time within the cross section, and the vertiport airspaces are similarly sized for only a single aircraft. Aircraft are assigned a separate origin and destination by uniform random distribution, with a trip starting time chosen by normal random distribution. The measures of traffic flow and key network metrics are calculated across the entire network of available airspace, which only includes the vertiport spaces and fixed route corridors connecting them, and not the restricted airspaces between corridors.

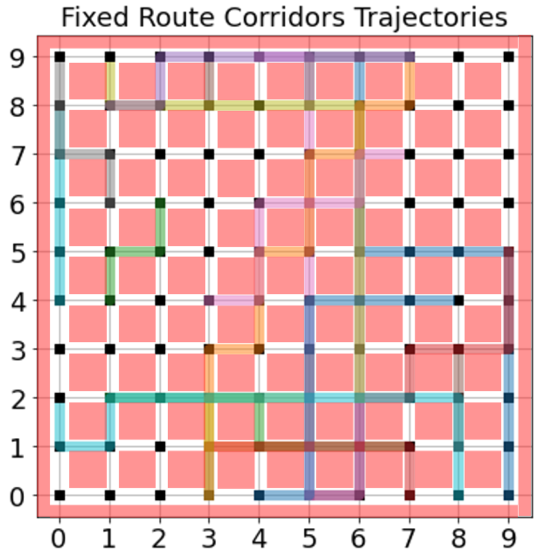


Figure 6.4. Top down view of the fixed route corridors network in the simulations. The colored lines represent aircraft trajectories, and the black squares mark the locations of vertiports.

Simulations

Each of the four networks described above were constructed in a simulation and the air traffic flow simulated in order to observe and measure it. The three simulations allowing for freedom of movement for the aircraft – unstructured network, geo-vectored network, free route corridors network – were simulated using the simulator tool developed in chapter 3. This simulator calculates the trajectories of aircraft on a rolling basis and detects conflicts and resolves them in a decentralized manner using a non-linear optimization program. The corridors in the free route corridors network were established by creating arrays of “keep-out” airspace restrictions along their boundaries.

For the fixed route corridors network a separate simulation tool was established. The simulator in chapter 3 assumes that aircraft have navigational freedom to move around the airspace, and the conflict resolution system similarly solves for the best trajectory that is not restricted or conflicting with another aircraft. These assumptions are not appropriate for a system of fixed routes, and to force the simulator tool to establish fixed routes by using near-ubiquitous “keep-out” restrictions would be unnecessarily burdensome. Therefore, a separate simulator tool was used, with this tool based on the tool described for the tube network in Sunil et al. (2015). In this simulation the network is modeled as a series of connected spaces, with each space representing either a vertiport or a part of a corridor between vertiports. Each space may only contain a single aircraft at a time. Aircraft move through the network by transitioning from one space to an adjacent space. When an aircraft cannot transition to the next space on its route it remains in its currently occupied space. The aircraft follow a predefined shortest path route, which does not account for predicted congestion on the route. Aircraft trajectories are planned in their entirety at a single time, in order of the earliest trip starting time.

Each simulation was run several times at varying demand levels to collect more results and reduce the effect of randomness on any network's results. Each simulation run represents 2.5 hours of operations, with time steps of 10 seconds. The results were aggregated into time bins of 5 minutes each, or 30 time steps. The maximum vehicle speeds were 100 mph horizontally and 5 mph vertically. Vehicles were spaced 0.55 miles horizontally and 0.1 miles vertically.

6.2 Key Network Metrics

The traffic flow measures – conflicts, density, actual speed, effective speed, effective flow rate – were calculated for each of the networks using the definitions described in chapter 3. However, the traffic flow measures do not capture all of the relevant information about network operations, which are more strategic in nature. Therefore, new metrics were devised and used to measure and describe the operations of the four networks simulated. These metrics represent the efficiency of the system, productivity, safety, and the concentration of operations, which pertains to the distribution of external costs such as noise around the network. Seven key network metrics were used, and each is described here along with its measurement and insights. The performance metrics are trip distance, travel time, share of available airspace, network capacity, conflict rate, concentration of conflicts, and concentration of trajectories. Using these seven metrics the networks are compared with each other to find the relative benefits and drawbacks of each network architecture.

Trip Distance

One measure of network efficiency is the distance traveled between an origin and destination relative to the minimum possible distance. Efficient networks will in general create trip distances close to the minimum possible distances, while inefficient networks will require significant extra distance in order to complete the trip. For example, in an unstructured network it is possible for aircraft to fly directly to their destination, without detouring around restricted airspaces, meaning that the trip distance is close to the minimum possible. Yet for the fixed route corridors network each aircraft must follow the corridor routes in the grid pattern instead of proceeding directly to the destination, creating extra distance travelled. The trip distance is important for operators and planners to consider because flying extra distance will require more energy and longer travel times, each a significant drawback.

There are two components of extra trip distance, an extra routing distance required due to the shape of the network and the minimum possible distance on the network, and an extra congestion distance due to tactical detours made along the route from conflict resolution. These two components are measured separately. The extra routing distance was computed by comparing the average route distance (the minimum possible distance along the network) for vehicle trips on an uncongested network with the average literal (Euclidean) distance between the origin and destination for the vehicle trips. This calculation was done as a ratio in order to create a growth factor representing the expected extra distance required due to the network shape for each network. The calculation is shown in equation 6.1. The growth factor for each network was then applied to a standard 10-mile (direct) trip between an origin and destination to create an expected minimum trip distance along each network.

$$Extra\ routing\ distance = \frac{Average\ route\ distance}{Average\ point\ to\ point\ distance} \qquad \text{(Eqn 6.1)}$$

The extra congestion distance was calculated using the traffic flow measures. By taking the ratio of the average actual aircraft speed (v) and average effective speed (e) an excess movement growth factor was found, which represents the average extra movement of the aircraft that did not move the aircraft towards its goal. This calculation is shown in equation 6.2. This excess movement factor could then be applied to the distance of the standard 10-mile trip along with the extra routing distance to establish an expected trip distance.

$$Extra\ congestion\ distance = \frac{v}{e} \qquad \text{(Eqn 6.2)}$$

By considering both the extra routing distance factor (ERD) and the extra congestion distance (ECD) factor together it is possible to calculate an average trip distance for the network that combines both effects. This average trip distance calculation is shown below in equation 6.3. For calculations the pair distance is 10 miles, reflecting a standard trip between an OD pair that is 10 miles apart by direct distance.

$$Trip\ distance = Pair\ distance * ERD * ECD \qquad \text{(Eqn. 6.3)}$$

Travel Time

Another measure of network efficiency and the user experience is the average travel time. The travel time is the amount of time it takes to move from the origin to the destination. In this calculation it will only be the flight time between the origin and destination vertiports, excluding extra loading, unloading, charging, or take-off and landing times. Travel times are an important criterion for every transportation service. By minimizing travel times an operator can make their service more attractive for customers, serve more trips with a single vehicle, and reduce operating costs per trip.

Travel times can be calculated using the average effective speed measure. The effective speed measures only movement towards the destination, neglecting excess movement, making it well-suited for quickly calculating travel time for a trip of a specified distance. Travel times for the four networks are compared on the basis of the travel time for an average trip between an origin and destination 10 miles apart. The travel time is calculated by dividing the trip distance by the average effective speed, as shown in equation 6.4. However, the trip distance for each network is not necessarily 10 miles, the extra routing distance (see *Trip Distance* above) must be considered, and first a growth factor is applied to the 10 mile trip distance before the expected travel time can be calculated.

$$Travel\ time\ = \frac{Trip\ distance}{e} \qquad \text{(Eqn. 6.4)}$$

Share of Available Airspace

Each network incorporates varying levels of airspace restrictions, from no restrictions for the unstructured and geo-vectored networks, to significant restrictions for the fixed route corridors network. For a network with many restricted airspaces the share of available airspace will be smaller than for an unrestricted network. A smaller share indicates simply that the network is operating with less airspace, and accordingly the same number of aircraft on the network will create higher aircraft densities in the available airspace. When studying the networks and their impacts, it is important to consider the share of the airspace that the network utilizes. All else equal, networks with lower shares may have higher densities and lower capacities, however the presence of restricted airspace also indicates that some areas within the network are being protected from the aircraft on the network for safety or external reasons.

The share of available airspace is calculated as the ratio of the volume of airspace usable by aircraft in the network over the volume of airspace within the broader external boundaries of the network. This ratio is shown in equation 6.5.

$$Share\ of\ available\ airspace = \frac{Volume\ of\ available\ airspace}{Total\ network\ volume} \qquad \text{(Eqn. 6.5)}$$

Network Capacity

Network capacity, or the maximum throughput the system can handle, is a key supply-side metric for operators to consider when planning operations and serving demand. By considering the capacity and comparing it with the demand planners and operators can make better choices about what demand is served and how it is served. The ultimate network capacity is also a key metric when considering how to structure airspace. In low demand systems a lower capacity network that prioritizes other measures such as travel times may be a good solution. In a high demand system having a higher capacity will become more important.

The capacity of airspace is not just how many aircraft can fit in the airspace simultaneously after accounting for separation between aircraft. Instead, the capacity is the highest throughput or productivity of the airspace, which depends on the traffic flow and congestion in that airspace. Previous chapters in this thesis defined capacity as the maximum possible effective flow rate of aircraft in the available airspace. A similar definition is used here, where maximum throughput is determined from the trendline of a density-effective flow rate curve (the fundamental diagram). However, one key adjustment must be made to account for the differences in networks. The effective flow rate captures the throughput of aircraft in the available airspace while controlling for the amount of available airspace. This is measured in vehicles per hour per square mile. However, each network will have greatly different shares of available airspace, and these differences should be considered. Therefore, in equation 6.6 the maximum effective flow rate is multiplied by the share of available airspace to capture the maximum throughput of aircraft in the system, when considering both available and restricted airspaces in the system. In this way the network capacity better reflects the network in its totality by considering the differences in available airspace.

$$Network\ capacity = Share\ of\ avail\ airspace * Max\ Eff\ Flow\ Rate \quad \text{(Eqn. 6.6)}$$

Conflict Rate

Safety is always a key consideration for aviation systems. Safety applies to many aspects of aviation and can be measured in different ways. One especially relevant safety metric for air traffic flow is the conflict rate, which measures how many conflicting trajectories that must be resolved occur in the airspace. While conflict detection and resolution systems will be robustly designed and tested to handle UAM operations, higher numbers of conflicts will always raise the chances of a loss-of-separation or even a collision between aircraft (in addition to negatively impacting traffic congestion). To prevent congestion and improve safety it is desirable to keep conflict rates low, and therefore minimizing the conflict rate is a possible goal of UAM networks. The four networks constructed are compared with each other on the basis of conflict rate as a proxy for safety on the network.

The conflict rate is measured by first finding the count of pairwise conflicts between aircraft in the airspace within a specific time window. The number of conflicts can then be taken as a ratio with the volume of available airspace and length of the time window to find the conflicts per cubic mile-hours, which expresses the conflicts in the network independent of the volume of airspace or length of time studied (similar to the calculation in section 3.2). However, the conflict rate used here should acknowledge differing shares of available airspace on the network. Therefore, this conflict rate is multiplied by the share of available airspace to account for the smaller airspace volumes in some networks. Ultimately the calculation arrives at a conflict rate measured in conflicts per hour within the network. The calculation for conflict rate is shown in 6.7.

$$Conflict\ rate = Share\ of\ avail\ airspace * \frac{Number\ of\ conflicts}{Airspace\ volume * Time\ window} \quad \text{(Eqn. 6.7)}$$

Concentration of Conflicts (Bottlenecks)

One major issue that can arise within traffic networks is bottlenecks. In chapter 5 bottlenecks were shown to be major challenges for UAM networks because they condense the throughput into a smaller area and artificially raise the density in the process. While bottlenecks can cause negative impacts to traffic flow however, they are nonetheless useful as a transition airspace between a larger and smaller airspace or between two different structures of airspace. Within the free route corridors network constructed here there are bottlenecks at the entrance to each corridor, where the airspace transitions from an unstructured type to the corridor. When considering networks comprised of different types or sizes of airspace, bottlenecks will be key areas to identify and manage closely.

Bottlenecks are identified in the networks considered here so that their impact on the overall traffic flow can be discussed. Bottlenecks are viewed by finding the concentration of conflicts within the network, using heat maps of the conflict locations. The locations and severities of the bottlenecks can then be discussed and mitigation strategies considered.

Concentration of Trajectories

During operations a network will not necessarily distribute the operations or impacts evenly. Operations may be concentrated in specific high-demand areas, or on links between high-demand areas. However, operations can impose external costs such as noise and safety. Understanding where operations and these external costs are concentrated is important when considering the broader impacts of these external costs. Concentrations of trajectories can be used as a measure of the concentration of operations. The trajectories are made of an array of points, with each representing a position at a defined time. Aggregating these trajectories across time to find the concentrations in a given area can create a measure of how many operations were in the area and how long they were there. The concentrations are then viewed on heat maps of the network to locate the areas with the highest external impacts from the UAM network.

6.3 Network Results

Four networks are considered in this chapter, with each network representing a concept for structuring airspace. Unstructured airspace represents a base case with minimal restrictions, geo-vectored represents a network with minimal restrictions but with similar headings grouped together, free route corridors represents a network with moderate restrictions but still some navigational freedom within corridors, and fixed route corridors represent the most restricted network with fixed paths. Each of the four networks was constructed in a simulation tool (see section 6.1) and a number of simulations performed. The results from these simulations were used to measure traffic flow and the key network metrics so that they could be studied and compared. Based upon these results insights about the individual networks and the networks in relation to each other can be drawn. In this section the results from the key network metrics are explored for each of the network types. Section 6.4 then discusses the broader implications of the results and what they mean for UAM operators and planners. Section 6.5 concludes the chapter.

Trip Distance

The trip distance captures the average distance of a standard 10-mile trip on each network, where an origin and a destination are 10 miles apart. Because the structure of the network may not allow for direct routing to the destination, and conflicts along the trajectory may require detours, the trip distance for such a trip on each network is often greater than the minimum possible 10 miles. Figure 6.5 shows the average trip distance compared with the density of aircraft on the network. Each of the four networks is represented by a different color, with points representing simulated results and the curves depicting the trendlines.

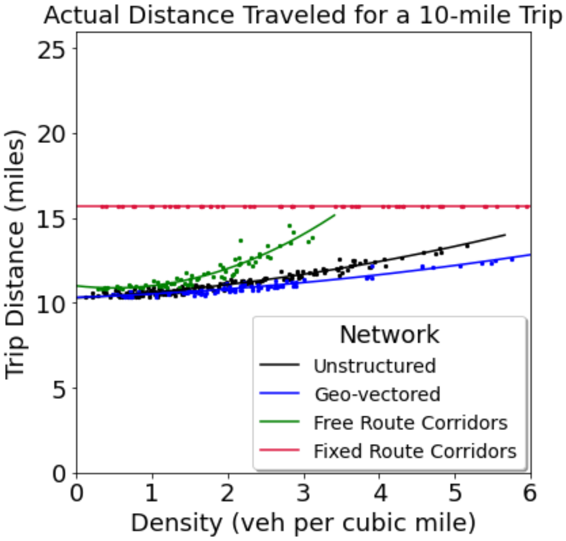


Figure 6.5. Expected trip distance along each network for a trip between an origin and destination 10 miles apart. The trip distance is compared with aircraft density. Points represent simulated results and curves depict the trendlines.

For each of the networks except the fixed route corridors the trip distance increases with the density of aircraft. This is because a higher density of aircraft creates more conflicts, and resolving conflicts can involve tactical detours, which in turn raises the average trip distance. The trip distance does not increase for the fixed route corridors because the aircraft are not allowed to detour from the assigned route and path. It is also noticeable that the low-density trip distance (representing the extra routing distance) in an uncongested network is 10 miles for the unstructured and geo-vectored networks, but somewhat or significantly greater for the free route and fixed route corridors networks. The two corridor networks have airspace restrictions that do not allow direct routing to the destination for many trips, and therefore even without congestion it will take longer to traverse the network to the destination. This routing inefficiency is greatest for the fixed route corridors network, which is shaped in a grid. The free route corridors network instead offers a closer approximation of direct routing to the destination, which reduces the trip distance in an uncongested state.

At higher densities the trip distances become longer because of extra congestion distance, which involves maneuvering around conflicts. The trip distances rise the quickest in the free route corridors network because of a bottleneck issue. The trip distances do not rise as quickly in the unstructured and the geo-vectored networks, indicating that conflicts resolved in those networks depend on tactical detours to a lesser degree. Interestingly, even at higher densities with congestion on the network the average trip distance is still longest for the fixed route corridors network, which speaks to the inefficiency of the grid network relative to other options which allow more direct routing. These results show that routing inefficiencies can have a significant impact on the average trip distance, creating trips that are 25% or more longer than the minimum possible trip. The additional distance flown represents lost travel time, excess energy spent, and excess maintenance incurred for each trip, all of which are desirable to avoid. Planners and operators will need to keep the routing efficiency and trip distances of the network in mind as they develop and manage UAM networks.

Travel Time

The average travel time, similar to trip distance, captures the expected travel time for a standard trip on the network between an origin and destination 10 miles apart. The time it takes each trip to be completed is a critical measure of the system efficiency, and ties in with the competitiveness of UAM service with other modes and the ability to maximize the number of trips per vehicle. The expected travel time is compared with aircraft density in Figure 6.6, where the results for each network are separated by color, the points represent the simulated results and the curves represent the trendlines.

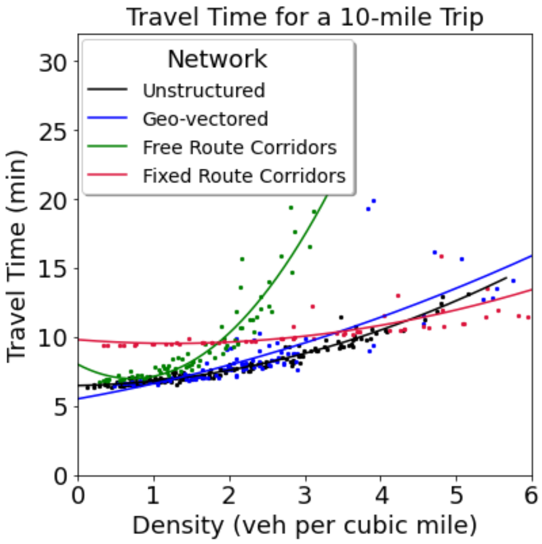


Figure 6.6. Expected travel times on each network for a trip between an origin and destination 10 miles apart. The travel time is compared with aircraft density. Points represent simulated results and curves depict the trendlines.

Similar to trip distance, the travel time will increase for all networks as the density increases. Rising density creates more conflicts on the network, and each conflict decreases the effective speed of the vehicle through either a detour or a delay. The expected travel time in an uncongested network, when the aircraft can travel at its fastest speed, are not the same however, due to the extra trip distance flown on the free route and fixed route corridor networks. In an uncongested state the fixed route corridor network has the longest expected travel times because of the extra distance flown, while the free route corridor, unstructured, and geo-vectored networks have shorter distances and travel times. For a network with low demand, the routing inefficiency that arises from the grid network and lack of navigational freedom on the fixed route network directly translates to lost travel time.

As the density of vehicles rise though, the expected travel times change and change relative to each other. Because of the bottlenecks in the system that significantly slow down traffic, the free route corridors network experiences the highest travel times of any network considered at a higher density. The unstructured and geo-vectored networks also see rising travel times, and close to their critical densities the expected travel times actually exceed the travel time on a fixed route corridor network. The travel times for unstructured and geo-vectored networks rise more quickly than for the fixed route corridor network because of their higher conflict rate. The end result is that while the fixed route corridors network may have routing inefficiencies that unnecessarily lengthen the travel times at low densities, at higher densities the low conflict rate of the fixed routes enables shorter travel times than the other networks considered.

As expected the results illustrate the significant impact of congestion on travel times. At higher densities the travel times on some networks increased by 100% or more, representing a severely congested network that could degrade the user experience. However, the travel times revealed an interesting dichotomy between travel times at low density, when routing efficiency is key, and at high density, when the impacts of the conflict rate and resolution become more important. With these results UAM planners and operators can carefully consider the relationship between the network design and travel times. While routing efficiency is important, the conflict rate and traffic congestion are also important considerations, and the ultimate balance between the two depends on the level of demand on the network.

Share of Available Airspace

An important descriptor of the network is the amount of airspace that is usable for traffic flow. Networks with many airspace restrictions will have smaller shares of available airspace, which will create higher vehicle densities given the same number of vehicles in the same broader region. The share of available airspace can be found simply by dividing the volume of available airspace by the total volume of airspace (including restricted airspaces) in the region. This ratio can be used to compare networks and metrics for the networks that depend on the amount of airspace.

There are four airspace networks considered in this work, and the share of available airspace for each is shown in figure 6.7. The unstructured and geo-vectored networks have the largest shares at 100% available, because each network does not include any airspace restrictions. The free route corridors has roughly 55% available airspace, due to the large restricted areas not usable for traffic in between the wide corridors. At the lowest end the fixed route corridor network has slightly more than 40% available airspace because of the widespread restrictions in the network and the narrow corridors available to traffic.

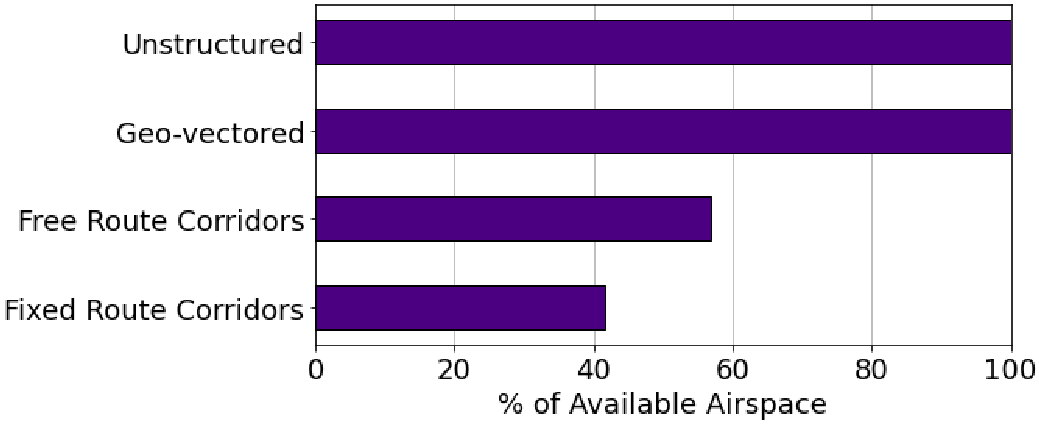


Figure 6.7. Shares of available airspace in each network.

While a higher share of airspace may be generally desirable for the routing efficiencies and capacities that are achievable with it, it is not always possible to have a network with a high share of available airspace. Many urban airspaces are marked by numerous flight restrictions, and UAM networks may need to be able to operate around those restrictions. Therefore it is important to consider how networks with high shares of restrictions might operate, and how they might be designed to make the most of the available airspace.

Network Capacity

The network capacities, or maximum productivity of the network, were measured in order to better understand the supply-side constraint. Capacities represent an upper limit for how much demand can be served, and maximizing capacity is a factor in the trade-offs of designing an airspace network. Capacity in the networks simulated was measured using the effective flow rate of aircraft. When effective flow rate is compared with density it creates a fundamental diagram, with the maximum of the diagram representing a highest expected throughput of vehicles that can be achieved. The effective flow rate measures the throughput in each unit of airspace, however, rather than the total throughput in the network. Since each network has a varying share of airspace, in order to compare the capacities it is first necessary to multiply the effective flow rates by the share of available airspace (see equation 6.6).

The fundamental diagrams, or effective flow rate-density relationships, for each network are compared in figure 6.8. The network types are differentiated by color, with the points on the plot representing simulated results and the curves representing trendlines. The maximum point on each curve is considered to be the capacity, and it is immediately noticeable that the free route corridor network has the lowest capacity. The free route corridor network experiences issues with congestion at bottlenecks as density increases, impacting the throughput, and the share of available airspace is relatively small, with the result being that adding vehicles to the network quickly congests a small usable airspace. In comparison the fixed route corridor network, which has less available airspace, has a considerably higher capacity due to its low conflict rate. At the highest end of capacities are the two unrestricted networks, which enjoy shares of 100% available airspace that allow for more aircraft to move through the network simultaneously.

The critical density of each network, or the density at which the capacity is reached, are also notably different. The congestion issues that affect the free route corridors network create a relatively low critical density. The other restricted network, the fixed route corridors, have the highest critical density which reflects the low conflict and congestion rate on that network. While the fixed route corridors network is not easily congested, it still does not have the highest capacity however. The fixed route corridors routing inefficiency slows the effective speeds (represented as the initial slopes of each curve) such that it requires a higher density of aircraft on the network to achieve the same throughput as the unrestricted networks.

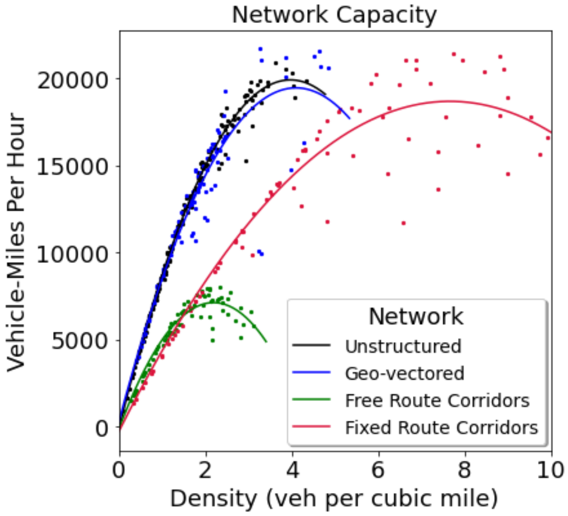


Figure 6.8. Network capacities compared using the throughput of vehicles with the aircraft density. Points represent simulated results and curves depict the trendlines.

At the highest level these capacity and fundamental diagram results demonstrate that the unrestricted networks comprised of the unstructured and geo-vectored networks yield the highest network capacities, which is obviously desirable for a potentially high demand system. A closer view reveals more nuance however, demonstrating that a fixed route corridor network can achieve similar throughputs to the unrestricted networks, albeit with higher network densities. These findings therefore represent a trade-off for operators between maximizing the absolute throughput on the system, or maximizing the density of the system before capacity is reached. This choice must also be weighed against the other performance positives and negatives of each network.

Conflict Rate

The conflict rate of the network serves two purposes: first as a measure of safety, because higher numbers of conflicts represent more chances for loss-of-separation events and more conflict resolutions that must be managed safely. The second purpose is as an indicator of traffic flow, because conflict resolution negatively impacts traffic flow by introducing detours or delays for vehicles. Accordingly minimizing the conflict rate in airspace is a common goal across many forms of aviation, but especially in high-density networks of UAM service. By minimizing the conflict rate UAM networks can reduce the risks of interactions between aircraft, and improve the traffic flow speeds and throughput. The conflict rate measure for the networks simulated compares the count of pairwise conflicts between aircraft with the length of time over which the counting was done. Higher conflict rates indicate that more conflicts occur in each unit of time.

The conflict rates for each network are compared with density in figure 6.9. The scattered points represent the simulated results, the curves are trendlines, and the different colors signify the different networks. The conflict rate increases at a quadratic rate with the density of aircraft, which is the same pattern that was observed for local air traffic flow, and one demonstration of the importance of lowering aircraft densities. The conflict rates are actually lower for the two forms of corridor airspace, in part due to the smaller available volume of airspace. The lowest conflict rate is seen in the fixed route corridor network, which maintains very low conflict rates even at high densities by using fixed routes that prevent any in-crossing conflicts with other vehicles. With the construction of the fixed routes and uniform maximum speeds for the vehicles, the only conflicts that can arise on the network occur initially at the intersections and vertiports, although these conflicts may cause congestion that spills onto the fixed route corridors. The next lowest conflict rate is found on the free route corridors network, which similarly aligns aircraft headings in the corridors to reduce in-crossing conflicts and achieve lower conflict rates. However, this network includes regions of unstructured airspace and bottlenecks, each of which increase the conflict rate.

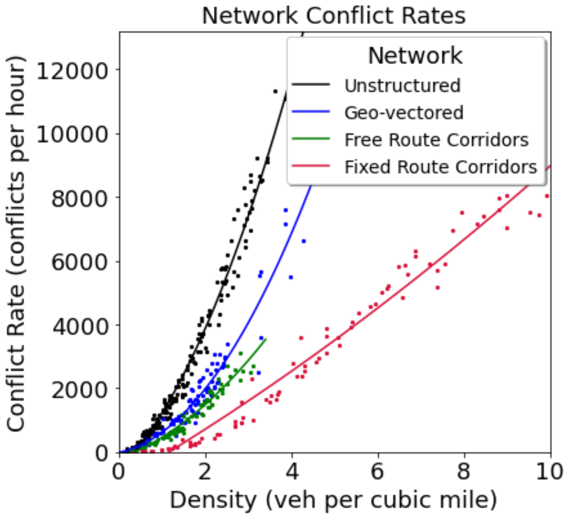


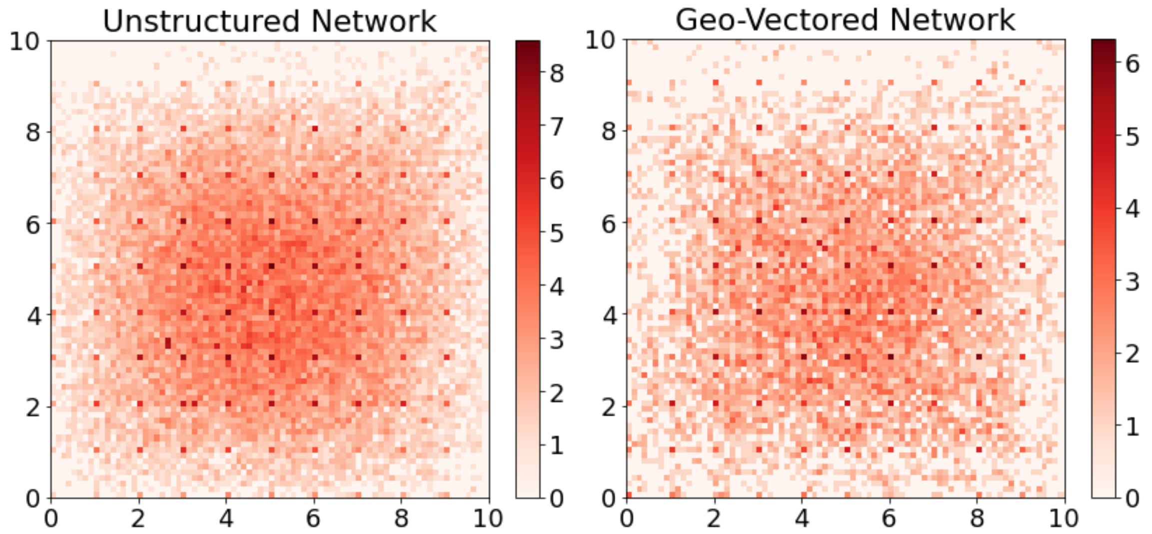
Figure 6.9. Network conflict rates compared with the aircraft density. Points represent simulated results and curves depict the trendlines.

The highest conflict rates are seen in the networks with the least restrictions: the geo-vectored and unstructured networks. While the geo-vectored network does introduce some alignment of headings and has a lower conflict rate, the unstructured network does not align headings and sees the highest number of conflicts of any network. When considering the numerous negative impacts to safety and traffic flow from a higher conflict rate it is important for operators and planners to consider ways to reduce the conflict rate. By designing networks with greater alignment of traffic flows the conflict rate can be reduced and safety on the network improved, as shown in the two networks that utilize corridors of airspace.

Concentration of Conflicts (Bottlenecks)

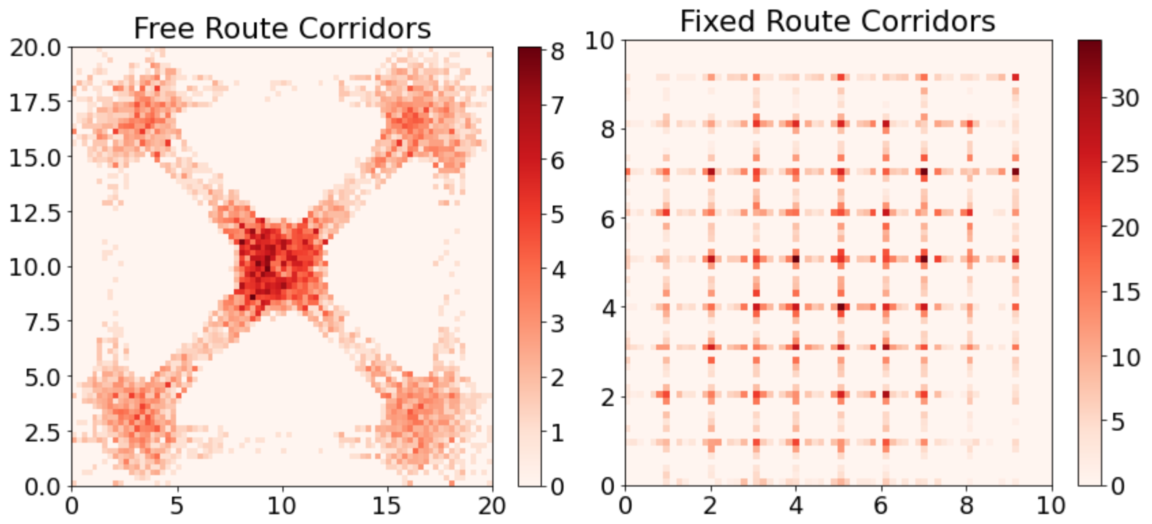
To better understand the behavior of traffic flow on the networks the concentration of conflicts on the network was viewed using a series of heat maps. By locating where the conflicts are it’s possible to identify bottlenecks within the network that could be improved to mitigate the conflict rate and the impact of these conflicts. Figures 6.10, 6.11, 6.12, and 6.13 each depict the concentration of conflicts for one network. Darker shades indicate more conflicts, while lighter shades indicate fewer conflicts.

Figures 6.10 and 6.11 show the conflicts for the unstructured and geo-vectored airspaces, respectively. The lighter shades and similarities across the majority of each map demonstrate that conflicts are relatively evenly spread across the networks, with no region of the maps accumulating noticeably more conflicts. However, the dark-shaded boxes that appear near vertiports do suggest that there is some level of bunching of conflicts near vertiports. Since vertiports represent the entrances and exits to and from the network it makes sense that vehicles would cluster near them and create more conflicts. This result highlights the need for effective air traffic management near vertiports.



Figures 6.10 and 6.11. Heat maps of the conflict locations for the unstructured network (6.10, left) and the geo-vectored network (6.11, right).

Figure 6.12 contains the heat map for the free route corridors network, which shows considerably more variability in the spread of conflicts. The dark spots near vertiports again shows the clustering of conflicts. However, conflicts also cluster near the corridor entrances where bottlenecks are formed and in the central region of the airspace, where there are vertiports in addition to an intersection of corridors. Bottlenecks such as the ones near the corridor entrances and exits were shown in chapter 5 to be problematic, primarily by condensing the traffic flow into an artificially high density. Accordingly, network designers may wish to change the network shape to mitigate these bottlenecks or to closely manage them. Similarly a change in network shape or operations could mitigate the concentration of conflicts in the central region. Finding alternative routing to avoid the area could improve the traffic flow both of bypassing traffic and traffic destined for the center.



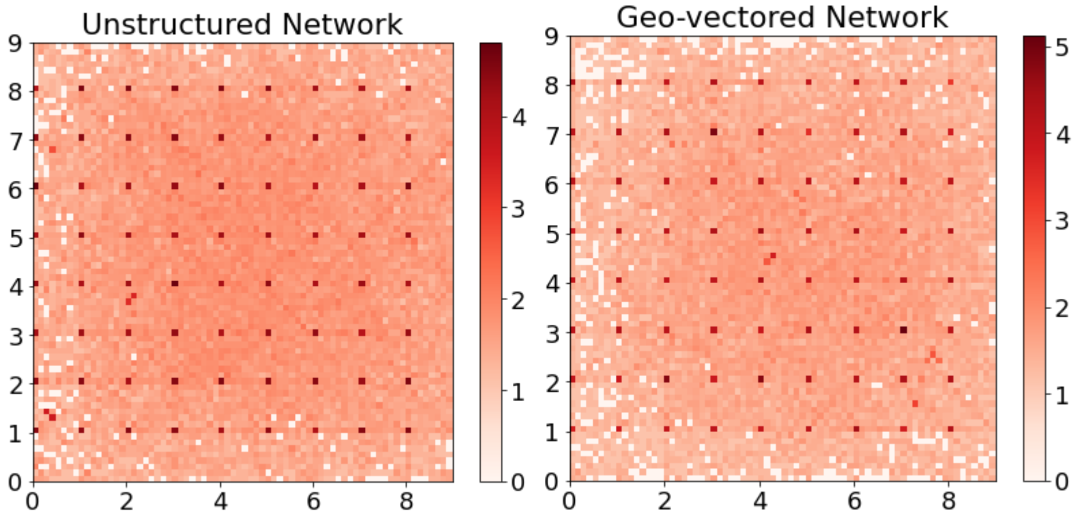
Figures 6.12 and 6.13. Heat maps of the conflict locations for the free route corridors network (6.12, left) and the fixed route corridors network (6.13, right).

The fixed route corridors network also shows a concentration of conflicts in the center of the network in figure 6.13. Additionally, a higher density of conflicts can be seen at vertiports and intersections on the network, where aircraft could cross in front of other aircraft. Based on this result it could be determined that placing network intersections and vertiports – both of which generate conflicts for the network – at the same locations could worsen traffic congestion by concentrating the conflicts. A better network design might spread out the conflicts by relocating vertiports to be away from intersections. However moving vertiports away from intersections could further reduce the routing efficiency of the network, increasing trip distances and travel times.

Concentrations of conflicts indicate congestion on the network and bottlenecks, which have negative impacts for the traffic flow of the network as a whole. Different network shapes can create concentrations of conflicts, such as near vertiports, at transitions between airspaces, or at intersections. Although the solution for spreading out conflicts may not always be simple, because restructuring the airspace may create other trade-offs with routing efficiency or restrictions. While all network types saw some concentrations of conflicts, concentrations arose from varying sources for each network. The results from each network highlight a number of situations that could cause concentrations of conflicts.

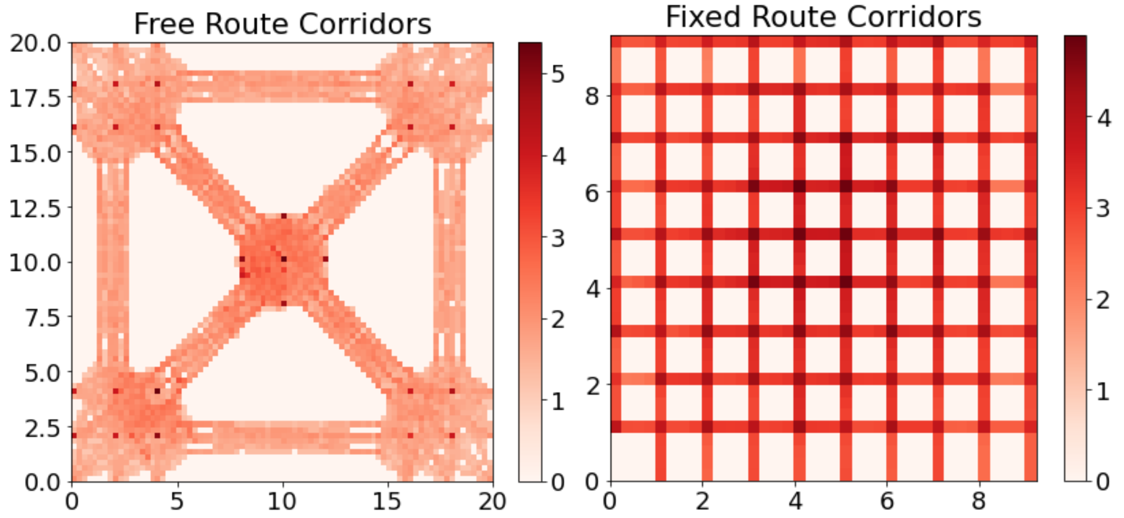
Concentration of Trajectories

UAM services will create some external costs such as noise, safety, or even privacy issues. Considering these, heavy concentrations of operations in specific locations around the network could impose unfairly high external costs on certain neighborhoods. Alternatively, if rules were devised to limit the operations in an area then a network with a higher share of operations utilizing that area will face a broader constraint on the network until the concentration of operations is dispersed. Each of the four networks operates with different routing, which can change where concentrations of aircraft are. Heat maps for each network showing the density of trajectories were prepared to explore how the networks might create higher densities of trajectories.



Figures 6.14 and 6.15. Heat maps of the aircraft trajectories for the unstructured network (6.14, left) and the geo-vectored network (6.15, right).

Figures 6.14 and 6.15 depict the unstructured and geo-vectored networks and appear very similar. The concentration of operations is relatively evenly spread except for near vertiports, where there is a higher concentration of operations. The fixed route corridors network in figure 6.17 shows a similar density of operations near vertiports, which simultaneously function as congestible intersections in this network. The concentration around vertiports also shows up in figure 6.16 with the free route corridors network. Although this network also shows heavier operations densities at the corridor entrances where bottlenecks occur.



Figures 6.16 and 6.17. Heat maps of the aircraft trajectories for the free route corridors network (6.16, left) and the fixed route corridors network (6.17, right).

These results indicate that probably the highest concentration of trajectories will come near vertiports, and appropriate consideration must be given for the neighborhoods surrounding vertiports. Such neighborhoods could be seeing hundreds or even thousands of operations each day depending on the network demand, and therefore minimizing the impacts of each operation in those areas will be important. Another result showed that the concentration of operations and congestion near bottlenecks and intersections may pose additional external costs for neighborhoods located near these airspaces. Planners of UAM will need to consider how these concentrations of trajectories will affect the local area and what mitigation measures to take, such as reshaping the airspace, rerouting some portion of aircraft, or implementing changes in the area to reduce the impact of each operation.

6.3 Discussion and Network Comparisons

In the work detailed above four different UAM networks were simulated, with each network representing a concept for structuring airspace. The unstructured network represents an unrestricted network with defined altitude levels and direct routing to destinations, but with no organization of aircraft by similar headings. The geo-vectored network constructs a similar unrestricted network, but does organize aircraft with similar headings into altitude levels. For more restricted airspaces two types of corridor-based networks were constructed. The free route corridors network mixed smaller unstructured regions of airspace connected by wide corridors that allowed for free routing within the corridors. The fixed route corridors network on the other hand connected a grid of vertiports by using narrow corridors with predefined paths for the aircraft to follow exactly. By studying each of these networks it is possible to look at the network level impacts of many different airspace structure and restriction concepts, including geo-vectors, corridors, intersections, vertiports, bottlenecks, and fixed routes.

The networks were compared with each other on seven specific metrics which captured varying aspects and behavior. Trip distances and travel times described the efficiency of the networks and the user experience. Shares of available airspace and capacity signified supply-side constraints for the networks. The conflict rate was used as a proxy for the level of safety in the network in addition to a factor in the traffic flow behavior. And the concentrations of conflicts and trajectories looked at the geographic variability around the networks and considered how different airspaces and areas might be affected. Taken together, these network metrics signify the broad trends and behaviors that can define networks of UAM airspace. This section discusses those trends and compares networks, using them to generate useful insights.

1. The first trend, and one that has been shown in previous chapters, is the significant negative impact of congestion for the user experience. The trip distance and travel time metrics each increased notably at higher densities on the networks during congestion. For some networks the travel times doubled or worse, and the trip distances rose by 25% or more. These values represent high potential costs to users and operators due to congestion. Longer trip distances and travel times will make operations less efficient and more expensive. There will be a need for planning and managing congestion on the network, in order to avoid the worst possible impacts. Network designs and operations could consider ways to alleviate congestion by dispersing operations over a wider area or time window or lowering the conflict rate for aircraft.
2. Density and conflict rates, and their negative impacts for traffic flow at high values, are another familiar trend to emerge from the results. This dissertation has well-established the significant negative effects on traffic flow that can come from high densities and conflict rates. There were several aspects of the networks that suffer from artificially high densities, and the concentration of conflicts. In the free route corridor network the transitions between unstructured regions and corridors created bottlenecks that concentrated trajectories and conflicts, slowing traffic in those

transitions and on the network as a whole. Additionally intersections of corridors such as the center region on the free route corridor network or the intersections on the fixed route corridor network concentrated operations and created higher conflict rates by misaligning trajectories. These areas of concentration are primary sources of congestion that degrades the performance of the whole network. On the fixed route corridors network conflicts at the intersections can spill over onto the corridors themselves.

3. One traffic flow and management issue that arose across all four networks was the concentration of operations and conflicts at vertiports. Because each network involved a limited number of vertiports, and the vertiports effectively serve as the exits and entrances to the networks, vertiports saw a high demand in every network and the heat maps revealed clustering of aircraft and conflicts near them. A possible solution would be to increase the number of vertiports or the capacity of each vertiport, although it may not always be feasible to given land constraints on the ground. Therefore, this trend highlights the importance of effective management of air traffic near vertiports. Effective air traffic management could mitigate these issues near vertiports without the need for potentially expensive or inefficient additional infrastructure.
4. The simulations revealed fundamental differences between unrestricted and restricted networks. Unrestricted networks allowed for direct routing and have more available airspace. They saw better routing efficiencies and could have higher capacities and a greater spread of operations by utilizing all of the available airspace. Conversely, restricted networks have routing inefficiencies and less available airspace. In the

results the restricted networks showed lower capacities and higher concentrations of operations because of the lack of available airspace. However, the restricted corridors are able to lower conflict rates by aligning aircraft headings, suggesting a safety benefit for restricted networks. Additionally, at higher densities network restrictions may serve to organize traffic in a more efficient method than unrestricted networks.

5. Among the unrestricted networks, geo-vectored networks appear to be more efficient than unstructured networks. Each have the same routing efficiency from allowing direct routes to the destination, but by grouping similar headings together the geo-vectored networks achieve a lower the conflict rate and improve traffic flow relative to the unstructured networks. These benefits translate into shorter trips distances and faster travel times and a better user and operator experience at higher densities. The findings therefore suggest that aligning aircraft headings, even in an otherwise unrestricted network, could be a worthwhile task from a traffic standpoint. Aligning aircraft headings and separating by altitudes seems a particularly effective strategy, because it produces an improved organization of the airspace without creating restrictions to the horizontal movement of aircraft which could compromise routing efficiency.
6. A trade-off between less restrictions and free routing versus more restrictions and fixed routing was found when looking at the restricted networks. Free routing through the corridors allows for better route efficiencies at low densities. However, it can create bottlenecks or congestion issues at high density, which was seen in the simulations. Fixed routing suffered from the greatest routing inefficiency in the simulations, but the fixed routes lower the conflict rates considerably. The fixed route

corridor network was better suited for high density operations, where it had lower trip distances, travel times, conflict rates and a higher capacity. When designing a restricted network that will use corridors the trade-offs between the free and fixed routing will need to be considered. Free routing also may require more available airspace because of the wider corridors, while fixed routing can operate with narrower corridors and less available airspace. Ultimately fixed routing could be a good solution for highly restricted and high-demand urban centers, while free routing could provide better service in lower-demand areas that still have some restrictions such as suburbs.

These points explain the broad trends and takeaways observed from the network simulation results. There are other more detailed and individualized takeaways that could be discussed (some of which were mentioned in the results section). Yet the goal of this chapter was to study and identify broad impacts from airspace structures and restrictions at the network level. And some of the individualized results may only apply to networks within that narrow context.

6.4 Conclusion

Chapter 6 has constructed and simulated a series of UAM networks representing varying concepts of airspace structures and restrictions. Using these networks traffic flow results were measured and key network metrics computed to compare the various networks, observe broad trends, and find insights that could be useful to UAM planners and operators of future networks. The results and metrics revealed a number of impacts that arise from different networks, and several broad trends were discussed based on these impacts. The findings indicated that densities, conflicts, and concentrations of operations have large impacts on the traffic flow developed and the user experience. Reducing these should be a primary goal when designing or managing a network, especially near areas prone to high concentrations such as bottlenecks, intersections, or vertiports. It was noted that unrestricted networks tend to have advantages in routing efficiency and capacity, albeit with a higher conflict rate. Among the unrestricted networks a geo-vectoring scheme was effective at reducing the conflict rate and improving traffic on the network. For the restricted networks a free routing concept through corridors improved routing efficiency at low density relative to a fixed routing concept, but at high densities it was more prone to congestion. Therefore a trade-off exists between free routing and fixed routing networks.

Several limitations apply to this chapter, including the context and geometry dependency of the networks and traffic flow behavior on the networks. While the networks presented by no means represent all possible forms of an UAM network, they were chosen and constructed to demonstrate the effects of different concepts and different airspace restrictions. The findings should not be taken as hard rules as much as a framework for identifying issues that might arise within an airspace network. Other limitations applied to the simulations used in the chapter, such as only simulating the cruise phase of flight and excluding the ascending and descending phases. It was noted in this chapter that traffic management near vertiports could be a challenge in the future, although this simulation has only simple abilities for modeling such traffic.

Future work could improve on the network simulation and modeling by incorporating more phases of flight. The networks could also be expanded by examining networks without pre-assigned altitude levels. Lastly the routing on the networks was done on a shortest-path basis, without including the effects of congestion.

Chapter 7

7.1 Summary

As advanced air mobility (AAM) develops as a mode there will be new entrants to the airspace that operate in different ways than traditional aviation. Since AAM can offer improved travel times relative to existing ground modes there is potential for high levels of demand on the airspace, involving hundreds or thousands of operations within an urban region simultaneously. With such levels of demand managing the air traffic will become critical, and this dissertation works on the air traffic flow management problem specifically in the context of AAM.

An initial issue with air traffic flow is understanding how it behaves. Macroscopic air traffic flow models are developed in chapter 4 by applying traffic flow fundamentals from other modes to the aviation context. These models relate the density of aircraft (demand on the airspace) to a number of key traffic measures such as conflicts, aircraft speeds, and throughput. The models depict the overall pattern of traffic behavior that arises at varying levels of congestion. The models also incorporate key operational parameters such as the spacing requirements between aircraft, the maximum speeds of aircraft, and similarity in headings between aircraft. The air traffic flow models can form the basis for an air traffic flow management system because they can be used to conceptually describe the trade-offs made in traffic management, and plan for and predict future traffic flow conditions.

The air traffic flow models were validated using simulated results, with the simulator developed and described in chapter 3. The agent-based microscopic traffic simulator progressively plans the trajectories of aircraft and detects and resolves conflicts using a decentralized system that reflects the future flexibilities of the airspace and system. The traffic flow within the simulator was measured using the metrics in chapter 3 to describe how traffic behaves within the system. The congestion patterns of the air traffic flow models were shown to emerge from the microscopic simulator results in chapter 4.

AAM traffic flows will exist within structured networks of airspace. Initially NASA and the FAA anticipate a network of designated AAM corridors that can separate AAM traffic from other forms of aviation. In the long term the corridor networks may expand or give way to more flexible forms of airspace. Chapter 5 studies how such airspace restrictions impact the traffic flow at a local level. A series of simulated experiments are conducted to explore the ways in which traffic flow is impacted by different airspace structures. The results identify benefits and costs to the use of airspace restrictions and are organized into a framework for thinking about the impacts of airspace structures. At a broader level, airspace structures will create network architectures that affect the performance of the system. In chapter 6 four samples of network architecture were constructed and compared across seven key performance metrics to demonstrate compromises made when designing such networks. The findings in chapter 6 showed that no single network design dominates the others, each network has benefits that vary with the demand level. Therefore setting the proper context and priorities for the system will be important before designing a network.

7.2 Contributions to the Literature and Applications

The work done here makes a number of contributions both to the academic literature and to real-world applications. The primary overall contribution is the application of traffic flow concepts and fundamentals to an air traffic flow problem. Previous research in air traffic management has generally focused on ATC interactions, tactical or strategic conflict resolutions, or managing link and sector capacities on airspace. AAM operations will require a new air traffic paradigm however, one in which congestion of the network and airspace may be an important issue. The air traffic flow models and concepts developed in this work promise to improve the understanding of air traffic flow and congestion behavior and suggest methods for mitigating congestion in the airspace through various strategic or tactical operating and design choices. Additionally the frameworks laid out in this paper can serve as a starting point for more advanced research into air traffic flow problems, with the ultimate aim of maintaining safety in the airspace and maximizing the efficiency of the system.

Much of the dissertation centers around macroscopic air traffic flow models. Building off of previously developed conflict probability models theoretical relationships between demand on airspace (density) and traffic outcomes (speed and throughput) are created. Previous literature on this area of multi-dimensional traffic flow has been limited by several factors or simplifications and the author is not aware of any work that goes so far to provide theoretical macroscopic air traffic flow models. The expansion of these models represented a research need because previous representations of air traffic flow either failed to capture the behavior of congestion on the system or to account for the numerous variables and parameters (such as conflicts, speeds, spacing requirements, and aircraft headings) that affect traffic flow. These works provided more limited partial views of air traffic flow and the traffic predicted or simulated using them is not a fully accurate description of air traffic flow. One application of this research is to improving the simulation of air traffic flow in existing research to provide more realistic traffic behavior.

There are numerous other applications that apply directly to real-world planning and operations. AAM planners, policy makers and operators can use these air traffic flow concepts revealed by the models when designing policies and airspace systems. The models will improve the understanding of potential traffic and congestion issues in airspace, allowing for an improved planning process. Examples of useful findings for planners include the delineation of the trade-off made between minimum spacing requirements and traffic flow conditions and that maximum speed limits may be warranted in high-demand airspace as a conflict-reduction method. Each of these insights and many more like them generated in the dissertation outline potential issues in the future AAM system and point towards mitigation strategies. Furthermore, the models can then be applied to operations of airspace to improve the tracking and prediction of future traffic flow conditions. An ability to predict future changes to traffic flow conditions will be crucial for the safe and efficient operation of AAM services because it enables operators to foresee congestion problems and actively work to mitigate them.

The traffic flow models in chapter 4 also opened the door for sensitivity analyses of the impact of contextual parameters on the traffic flow. While previous literature recognized the importance of considering spacing requirements and other contexts, few if any provided robust sensitivity analyses that could describe how observed traffic flow conditions would change based upon changes in contexts. Planners and designers of the system will need to make certain compromises between objectives, such as between maximum allowable speed and conflict rate, and a model that can explain the shape of these compromises as these models do are useful for decision-making. The adaptability of the model to varying operating parameters also allows for rapidly updating traffic flow models in simulations and planning according to changes in the parameters.

In chapter 5 several experiments on airspace restrictions and traffic flow were conducted, and the behavior of traffic near airspace restrictions and structures was examined. This work further develops this area in which a limited number of previous works conducted similar experiments without a focus on traffic flow. By focusing on traffic flow and considering the findings a framework for the impacts of airspace restrictions on local traffic flow was then generated. Ultimately while the experiment results were generated from a few specific scenarios, the experiments were designed to demonstrate simple but key concepts that govern air traffic flow’s interactions with airspace restrictions. These concepts can then be brought forward into the policy and planning realm where they can serve as guidance for the design and planning of airspace structures with an eye towards efficient air traffic flow operations.

At the network level there were again a limited number of previous works that tested different network architectures in simulations. This work built upon and expanded these earlier studies by comparing a larger number of key performance metrics across the airspaces and considering the fully sensitivity of these metrics to demand on the system via density. The focus of this dissertation on traffic flow aided in producing the sensitivities of the results by identifying the relationships between the performance metrics and traffic flow measures and using these relationships to model the behavior of the performance metrics. Illuminating the benefits and drawbacks of each network architecture is another important development for the design of future airspace networks. While early airspace networks may consist of point-to-point corridors, the shape of these corridors and the future extension or molding of them is still under question. The network-level findings of chapter 6 show how different corridor shapes can be effective at different demand levels, and that less restrictive networks can also increase efficiency under many operating conditions.

The air traffic flow models can be applied to other uses, such as for air traffic flow management. Previous solutions of the ATFM problem have often used capacitated links or sectors of airspace, with a hard capacity imposed to represent the full congestion of the system. However such a formulation ignores the impact that density on the system has even at sub-capacity demand levels. A new formulation could improve upon previous formulations by including air traffic flow models to more accurately describe traffic in each sector. A more accurate representation of traffic has additional benefit of improving the solution once implemented as real-world conditions will align more closely with the predictions. While AAM planners can use this formulation to improve the design and simulation of airspace, the formulation would be a direct improvement for AAM operators or UTM service providers that will provide traffic assignment.

7.3 Limitations and Future Research

While this dissertation has taken a deep look at air traffic flow and covered a number of topics there are still further avenues for future research. While extensions off of the research were generally presented within each chapter, it is worth summarizing a few of the larger aspects here to provide a more complete view. Naturally the simulated nature of the results will always be ultimately insufficient and real-world demonstrations will be needed. Simulations were necessary for this work to conduct experiments that would otherwise be infeasible with current technology and resource limitations. As AAM service is expanded the technology matures however it will become worthwhile to conduct real-world experiments that confirm the findings from the simulations.

The air traffic flow models formed a core component of the work and their flexibility and sensitivity to operating parameters are a key feature. However, there are other aspects of the air traffic flow models that could be studied more closely. Specifically, the impact of conflict resolution methods on the models and traffic flow warrants future work. Chapter 4 discusses the importance of the speed loss per conflict parameter, which captures how each conflict negatively affects the airspace. While some insights into this parameter, its behavior and its impacts were found, a fully developed model for the parameter with validating experiments was not presented.

Future work in this area could improve upon this and in doing so improve the findings would indicate conflict resolution methods that could be particularly efficient for traffic and congestion.

The simulated experiments for airspace restrictions and structures could also be expanded in future work. Experiments could include further studies of different airspace restrictions and network architectures. While restrictions and networks will follow the general rules outlined in chapters 5 and 6, each new context may also present unique challenges that are worth identifying. Examples of potential new experiments include local traffic flow near vertiports (identified as a key area of the traffic management problem). At the network level a consideration of a network with different levels of corridor, akin to arterials, collectors and local roads, could represent compromise between restrictions and efficiency for a network.

A discretization of airspace was used in chapter 5 to provide a localized look at traffic flow. However no efficient method for discretizing airspace into sectors was established. Building off of existing literature a future expansion could consider different methods of discretization, including determining appropriate sizing for airspace sectors. While larger airspace sectors lose the detail that comes with local airspace sectors, smaller sectors may also fail to aggregate the traffic flow to a meaningful level for macroscopic traffic flow modeling.

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