Urban Air Mobility Airspace Dynamic Density Safety Metric

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NASA's Advanced Air Mobility (AAM) project focuses on enabling emerging aviation markets by accelerating development of safe, high-volume flight operations.[1] It involves development and validation of vehicles, airspace, and automation changes required to support concepts such as Urban Air Mobility, a vision for electric or hybrid electric, vertical or short take-off and landing vehicles that can transport passengers and cargo over an urban environment.[2] NASA's System Wide Safety (SWS) project is coordinating with AAM by understanding how safety could be affected by these emerging operations. We approach the assessment of airspace safety by identifying threats to operations and then monitoring and predicting the evolution of those threats encoded in a set of safety metrics.[3]Toward this end, we have been developing a dynamic density metric to predict the likelihood of vehicle conflicts in the airspace.

I. Nomenclature

SWS	=	System Wide Safety
AAM	=	Advance Air Mobility
DD	=	Dynamic Density
UAM	=	Urban Air Mobility
ETA	=	estimated time of arrival
ETD	=	estimated time of departure

II. Introduction

In sociology, dynamic density (DD) refers to the combination of population density and the amount of social interaction within that population. The concept of DD is used in traditional (manned) aviation to predict the workload of air traffic controllers. Considering not just the population density (i.e., number of flights in an airspace volume) but also the interaction of the flights is necessary because one of the top contributors of Air Traffic Controller taskload is keeping flights well separated from each other and from any restricted airspace; the interaction between flights makes that task more challenging. The traffic characteristics that are most relevant to accurately predicting controller workload have been well studied and numerous combinations have been empirically shown to have varying levels of predictive success.[4-6]

The idea of DD may also be applicable to UAM. Unlike traditional aviation, UAM operations will likely primarily be controlled by automated systems, not humans.[7] Thus, controller workload is not anticipated to be an issue (except perhaps in the initial phase of UAM implementation when humans may be much more involved than once UAM is mature). Conflicts between flights will remain an issue, however, and excessive deconflictions may lead to an unsafe state due to unanticipated energy (battery) depletion or other vehicle health related issues. Additionally, the number of conflicts must remain within computationally-manageable levels.

Much like in traditional aviation, considering either population density or amount of interaction within the UAM population alone is insufficient. The population density could be low, yet if much of the population interacts in a

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confined area within a small duration, potential conflicts are increased. Alternatively, the number of potential conflicts is expected to be low if the population density is high but the flight paths are well separated.[3] It is interesting to consider whether the population density is even required. We believe that it should be considered with the rationale that low density both facilitates primary deconfliction and also reduces the likelihood of secondary conflicts.

To determine the UAM traffic characteristics that increase conflict rate, we conjecture from the literature a UAM traffic management concept of operations [2,8] and make the following assumptions:

(1) The DD metric is used for preflight planning to plan the route and determine required energy reserves. A proposed flight plan (including, at least, waypoints, estimated time of arrival (ETA), and estimated time of departure (ETD)) are provided to the traffic manager.
(2) The traffic manager decides how many flights to clear into an airspace, partially based on the DD metric.
(3) Each flight uses onboard conflict resolution capability to avoid separation violations (as well as other threats).
(4) UAM is used for air metro. That is, aircraft only travel between established vertiports. Arbitrary point-to-point air taxi or delivery operations are out of scope for this iteration.

III. Dynamic Density Safety Metric

Driving on the highway during congested periods involves similar concerns and serves as an analogy to facilitate the analysis of important UAM traffic characteristics. Drivers decides whether to take the highway or side streets based on the expected congestion and their required destination ETA (and if they are running low on fuel, that too is considered), paralleling the operation of assumption (1). In driving on the highway, the ramp meters serve to regulate the number of vehicles entering the highway, a weaker version of assumption (2). Finally, once on the highway, each driver (or autonomous vehicle) maintains their own separation from others, analogous to assumption (3).

A number of traffic characteristics correlate positively with highway dynamic density, including the following:

- The number of vehicles expected along the route
- Lane closures due to construction or an accident
- Special operations, such as an approaching emergency vehicle or a reckless driver
- Merging traffic from on-ramps[4]
- The number and proximity of vehicles near the driver's vehicle[5].

Next, we consider how ramp meters help manage dynamic density. The goal of metering is region specific. It can be used to increase traffic speeds for those already on the highway, reduce overall travel time for everyone, reduce collisions, or reduce emissions by favoring the carpool lane. Toward safety benefits, the Federal Highway Administration describes the role of ramp meters as "break[ing] up platoons of vehicles entering the [highway] and competing for the same limited gaps in traffic. By allowing for smooth merging maneuvers, collisions on the freeway can be avoided. Many regions have reported significant reductions in crash rates after starting ramp metering."[9]

Contemplating the similarities of drivers (or autonomous vehicles) each interdependently making their way through common potentially congested corridors and UAM flights crisscrossing an urban area, we extrapolated the DD factors that we believe affect UAM safety. These factors, listed in Table 1, will be substantiated through comparison with conflict rate during validation testing.

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[3] "Does segregation of flights matter?" is an open question. ATC workload is certainly affected by well-behaved streams of traffic, each stream segregated by aircraft type, airspeed, and heading. People are good at finding patterns and utilizing those patterns to reduce workload. Our assumed planner is not planning for clusters of flights together, but rather for each individual flight in a population of many clusters. Hence, we are excluding the segregation factor.
[4] Merging traffic creates the potential for conflicts and results in either path changes (lane change) or speed changes
[5] Number and proximity of nearby vehicles both indicate how well conflicts can be avoided and how efficiently they can be alleviated.

Table 1: Airspace characteristics that contribute to UAM dynamic density safety metric.

Factors	*Sub-factors*	*Rationale*
Airspace Density	Number of aircraft	Flight paths more likely to interfere if more aircraft are in the airspace
	Airspace dimensions	Smaller airspace can support a smaller number of aircraft
	Unusable/restricted airspace ("keep out zones")	Airspace not available to general population of aircraft due to obstacles, TFRs, SUA, adverse weather (e.g., thunderstorms), bad nav/comm reception areas, etc.
	Aircraft buffer ("peripersonal space")	Larger required buffers[6] ('standard separation' airspace appropriated for an aircraft) will fill up the space more
Aircraft Proximity	Distance to nearest neighbors	Tactical adjustments of flight path will increase probability of interference if flights are "too close", a distance specified by the user
	Local airspace density	Density in immediate neighborhood impacts effectiveness and efficiency of deconfliction. As flights near vertiports, local airspace density near ETA contributes to delays which in turn contributes to energy depletion
	Number of close pairs[7]	Increased probability of tactical re-planning, potentially leading to excessive energy depletion, airspace-wide
Special Operations (Emergency flights; Off-nominal flights) Disturbance Potential	Disturbance likelihood – external input from aircraft health prediction system or historical data	High likelihood of a special operations flight potentially increases probability of tactical re-planning
	Number of flights disturbed	Measure the ripple effect of a special ops flight entering the airspace
	Distance to nearest neighbors	Unexpected maneuvers will disturb nearby flights more than well-separated flights

The metrics listed in Table 1 are each safety metrics (SM) in their own right but could be easier to process[8] if combined into fewer metrics.

The factors and metrics shown in Table 1, as well as their combination into the DD safety metric are a conjecture. To determine the efficacy of the individual or combined metrics requires empirical validation. In the original DD work for manned (mostly commercial) aviation, human-in-the-loop studies were conducted and the computed DD was compared to the controllers' subjective workload ratings. We do not have that option for computer-controlled UAM. One approach that may be revealing is to conduct simulation studies comparing DD to the conflict rate. If the consolidated or individual metrics correlate well with conflict rate, the simulations can also guide selection of a DD threshold that is commensurate with an acceptable conflict rate.

In the paper, we will describe the computation of individual and consolidated metrics, results of validation testing, computational considerations, and visualization of the metrics. We will also describe the development environment, designed to be representative of the integrated demonstrations of realistic operational scenarios that will be conducted by AAM as part of the National Campaign (NC).[10]

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[6] Buffer dimensions are specified by the user and may vary depending on aircraft type or operations.
[7] Close pairs are defined as two flights within specified horizontal radius and vertical altitude. Can include multiple radii in the consolidated dynamic density metric.

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