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Entropy-based Design of Air Traffic Management

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The basis for the design methodology of future air traffic systems presented in this paper is making uncertainty management the primary and top-level design principle. Entropy measures the dispersion of probability distributions, and plays a central role in analysis of dynamic physical systems (e.g., thermodynamics) and information architectures (i.e., through information theory). Air traffic systems combine physical systems and information architectures to ensure safety while maximizing capacity. Physical systems, including air traffic flow and weather, generate positive entropy flows while information flows (e.g., command and control) are modeled as negative entropy flows. The principles for designing future ATM is developed based on entropy calculations. A quasi-conservation law is presented based on entropy flows for ensuring that the physical air traffic flow operates in regions of the dynamic state space that has very low probabilities of collision or flight through adverse weather while maintaining high capacity. The goal of these principles is to simplify the design of ATM architectures that are robust to exogenous events, and enable a top-down design methodology.

Nomenclature

I	=	information flow, uncompressed, measured in bits
N	=	negative entropy (negentropy) as defined by Shroedinger
S	=	entropy as used in statistical mechanics or information theory

I. Introduction

A. Objective

The objective of this paper is the conceptual development of principles for a clean slate design methodology for future Air Traffic Management (ATM), twenty years and beyond. Current air space usage is sparse and labor intensive. In 2011 an FAA workforce of 15,000 air traffic controllers handled on average 50,000 commercial flights per day, with only an estimated 5,000 commercial airplanes in US airspace at any moment. The volume of towered airport commercial operations is highly concentrated at thirty congested hub and spoke part 121 airports. The volume of general aviation towered operations is roughly twice that of commercial towered operations. However, on a passenger basis the thirty congested part 121 airports currently dominate passenger traffic compared to the twenty thousand airports (towered and untowered) supporting general aviation; a high level of concentration. Beyond the current general aviation airports, STOL (short takeoff and landing), VTOL (vertical takeoff and landing), and off-airport operations are at present minimal in the continental United States. Heterogeneous Alaskan airspace operations are indicative of the future potential of aviation in the overall transportation system.

The current airspce operational usage could potentially be transformed a generation from now, but in ways that are difficult to accurately forecast at present. For example, general aviation forecasts since 2006 have been unreliable[1]. Post-hoc analysis shows that declining numbers in the pilot population are a significant factor, as well as sensitivity to economic conditions. Nonetheless, it is highly likely that autonomous vehicle and related technologies will generate market forces for air space usage that will be quite different with significantly higher vehicle traffic flows

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than just the current dominant part 121 commercial flight hub and spoke operations. In part, this will be due to UAVs, and for personal transport, relieving the burden of obtaining a pilot's license or hiring a pilot. The technological hurdles and potential economic impact are similar to autonomous self-driving cars, which are expected within the next decade.

This paper aims for a clean slate design methodology for ATM that can accommodate future heterogeneous air traffic with potentially an order of magnitude increase in capacity while decreasing the need for direct control by human air traffic controllers, and minimally impacting trajectory efficiencies. The methodology is not targeted towards any one specific scenario of future airspace usage, though it does assume that a significant fraction of vehicles a generation from now can operate trajectory control algorithms that would be difficult with just human pilots and human controllers co-ordinating through low-bandwidth voice loops.

B. Motivation

In the United States, transportation systems and their principle modes of operations have been relatively quiescent since the 1980s. The 1980s saw the completion of the US highway transportation system, and the increasingly widespread automobile commute congestion characterized by traffic jams at merge points and lane reductions. For cargo movement, containerization allowed fluid transition between ship, rail, and truck – and dominates the transportation modes for goods. For airspace passenger movement, part 121 airline operations dominate business travel and a large fraction of personal travel. Kahn's 1978 airline deregulation act[2] led to the establishment of the hub and spoke airline model of operation. Together with Traffic Flow Management (TFM) introduced after the 1968 summer of congestion at the five busiest airports, the current pattern was established: congested hub airports that are metered by TFM especially during IFR runway operations. The runway capacity limitations at congested hub airports are the principle bottleneck in air space usage today. The runway capacity of 75 to 90 seconds per plane is principally based on safe single airplane occupation of runways, and approach spacing during IFR operations where attempted landings can result in missed approaches. The runway throughput limitations at these airports backs up to merge points at metered arrival gates, and through TFM to takeoffs at departure airports. In metropolitan regions with multiple major airports, competing arrival and departure routes add another layer of complexity. In the many decades since the establishment of these modes of operation, there has been little change from the viewpoint of passengers or cargo movement.

In contrast to the last thirty years, the next twenty to thirty years will likely be disruptive and change US Transportation systems through autonomy and related technologies. It will be one of those periods in history where technology maturation and market forces combine to rapidly transform aspects of everyday life. The transformation is likely to be of similar magnitude to the information technology revolution, which encompasses the personal computer (Time Magazine Person of the Year 1983), widespread use of the internet, and smartphones. The transformation will first occur in autonomous vehicle technology, and later in automated traffic management technology – which is the subject of the design methodology of this paper. The transformation will first occur in automobile technology, which is already underway, and later in aviation technology; with significant cross-over potential of technology.

C. Autonomy and US Transportation Systems

The two principle factors factors by which autonomy will change US Transportation systems are economic and enabling new modes of high capacity traffic management.

1. Economic

Autonomous vehicles will change the economic set-point (where supply meets demand) for rapid individualized transportation services compared to mass transportation. Self-driving cars will dramatically lower the operational costs for chauffered driving services such as taxis through automation. They will provide mobility on demand to people who do not have driver's licenses. Automation will enable vehicles to be rapidly fetched and hence relax the constraint of always having an individually owned vehicle parked within walking distance. Economic costs associated with land use patterns required for parking of automobiles will be lowered.

Most individually owned automobiles currently spend the majority of time idle due to lack of a human driver, automation will enable them to be used for running errands and delivering goods when not used for human transport. The higher rate of utilization will lower amortized capital costs on a per trip basis, further changing the economic set-point. Modes of ownership will diversify to best capture economic value.

As an aviation example, the cost of piloted helicopter package delivery is prohibitive for anything other than emergency supplies or for the extremely wealthy. However, several companies are already pursuing development of routine UAV package delivery, which is expected to be both economical and timely compared to today's van-based package delivery. For human transportation, analogous considerations for self-driving cars apply to self-piloting personal air vehicles, operating from commute distances upto hundreds of nautical miles. The direct-to routing and speeds that are multiples of surface vehicle speed will drive demand. In other words, autonomy will introduce new classes of vehicles and patterns of usage that are heterogenuous and require higher capacity traffic management than current ATM. For long distances on the order of a thousand nm or more, the fuel economies of large jet transports flying enroute with minimal drag near the boundary of the stratosphere will still be cost advantageous, even with human pilots.

2. Autonomous Traffic Management

Autonomy technology will enable efficient (high capacity and high safety) traffic management through trajectory control algorithms that are beyond the capabilities of human ATC directing human-at-the-controls. For self-driving cars, an example is MIT's proposed bilateral control[3] that would continuously adjust speed and relative spacing through vehicle to vehicle (V2V) communication. Bilateral control suppresses traffic flow instabilities. An algorithmic enhancement to bilateral control that incorporates anticipatory merge is reported in this paper in the context of aviation.

There is at present considerable speculation, controvery, and investment as to when fully autonomous self-driving cars will be available[4]. For the purposes of autonomous traffic management, production cars that are already available with Traffic Aware Cruise control, self-braking, and lane shifting meet most of the enabling criteria at least for highways. Higher-level traffic control algorithms – denoted Co-operative Adaptive Cruise Control (CACC), require these type of adaptive cruise control vehicles, and in addition vehicle to vehicle communication, and usually vehicle to infrastructure communication. Research and development on CACC algorithms that improve traffic flow capacity and smoothness have matured well into the advanced experimental phase[4]. Their deployement will depend on achieving a critical mass of automobiles that have the necessary capabilities as well as public policy, such as reserving what are now HOV lanes to CACC automobiles to achieve lane capacities that are multiples of the capacity of manually driven lanes.

For aviation, the human ATC-Pilot voice loop introduces large delays in command and control, as well as substantial uncertainty with respect to pilot intent and timing. An extreme example is pre-satellite oceanic Air Traffic Management, where low-resolution localization and infrequent communication (e.g., hourly) resulted in large spacing requirements and low capacity. Even as late as 1998, oceanic separation requirements were 100 nm miles lateral, 120nm longitudinally (15 minutes in trail), and 2,000 feet vertical.

NASA's Air Traffic Management Technology Demonstrations[5] that control airline arrival spacing through speed adjustments commands originating either through controller decision support tools (CMS) or advisory tools for pilots (FIM), are examples of aviation traffic control algorithms. They are deployable as decision aides for human in the loop operations, but point towards automation through coupled autopilots, as is being experimentally demonstrated.

II. Principles for Design of Air Traffic Management 2035 and beyond

This paper is a conceptual analysis towards the goal of developing methods for design of high capacity and high safety ATM for 2035 and beyond. The following subsections define the principle concepts.

A. Entropy Management

Entropy management is an uncertainty first approach to ATM Design. ATM design would be a simple exercise if there was no uncertainty in aircraft trajectories, weather, sensors for surveillance and navigation, etc. The difficult part of ATM design is to incorporate the means of actively managing this uncertainty, hence entropy management. The mainstream approach to air traffic management design is to develop a new air traffic operational concept, then a detailed deterministic simulation of large slices of the airspace with the new operational concept, and finally apply Monte Carlo analysis over parameter ranges such as weather or adherence to trajectories. At this stage, if the simulation is accurate enough, emergent properties are often discovered due to the various sources of uncertainty. As a consequence, the concept might no longer be viable or require enhancement for uncertainty management in the concept of operations. The principles described in this paper aim for a hierarchical refinement design approach, where uncertainty and the means of mitigating uncertainty are introduced from the very beginning.

Mathematically, entropy is formulated in statistical mechanics and information theory as a statistic on a probability distribution:

$$S = -k\sum_{i} p_i \log(p_i) \tag{1}$$

Through the mathematical development of statistical mechanics and information theory, entropy as an aggregate statistic is deeply interwoven into physics, communication theory, system dynamics, and machine learning. For thermodynamics, entropy has the units energy/temperature, k is Boltazman's constant, and the probability distribution is on energy levels of particles. The log is natural log (base e). This probabilistic formulation was developed in the second half of the nineteenth century, and shown to be equivalent in the aggregate to the formulation in classical thermodynamics. For information theory, entropy is dimensionless and measured in bits (for base 2 logarithm), or in nats (for base e logarithm), k is unity, and in most formulations the probability distribution is defined abstractly on discrete alphabets. Entropy and its dynamics can be applied to any probability distribution. For air traffic management, distributions related to separation assurance and collision avoidance are most relevant. Our formulation is meant to encompass probability distributions for uncertainty in air traffic, weather, sensors, and system reliability. Unless stated otherwise, in this paper we will mainly be focused for traffic on distributions of distances between vehicles, not the kinetic energy of vehicles. Nonetheless selected results from statistical mechanics can be applied, but with the caveat of avoiding inapplicable assumptions such as conservation of energy. Other probability distributions for air traffic, such as *Tau* (time to closure) are being considered for future work.

Entropy is additive, and command and control counterbalances processes that lead to disorder, as explained below. Conceptually, an air traffic system needs to be designed to meet the following constraint:

$$\sum_{p} S_p \leq N \leq I \tag{2}$$

The summation is over the sources and processes that lead to entropy, including traffic, weather, and sensors. For statistically independent sources of entropy, the left side summation is an exact composition for the cumulative entropy. N is negative entropy, as defined below, and corresponds to the air traffic management command and control that manages these cumulative disorderly processes. N is the effective decrease in the dispersion of the probability distribution; if it is not sufficient then entropy of the air traffic will increase resulting in unacceptable levels of near mid-air collisions. I corresponds to the actual communication bandwidth between traffic management and vehicles, and vehicle to vehicle communication. It also includes the sampling rate for surveillance, which is modeled as a communication from plane to air traffic control. Examples are pilot position reporting, radar transponders, or ADS-B. The difference between I and N depends on a number of factors, including the Shannon entropy of the communication (i.e., compressibility of the communications as well as noise in the communication channel), and the effectiveness of the algorithms that use the communicated information to reduce the entropy of the air traffic probability distributions. For example, bilateral control[3] for CACC is far more effective than unilateral control in suppressing traffic control instabilities, even after adjusting for twice the communication channels.

While equation 2 provides overall bounding constraints on the design of an air traffic system, the following equation provides a differential time and space equality constraint that can be applied for finer-grained dynamics. It is closely related to equations for the thermodynamic entropy dynamics of weather.

$$\frac{\partial S}{\partial t} = -divJ_S + \sigma - N \tag{3}$$

This partial differential equation describes the time evolution of entropy at a point as influenced by flows from the surrounds (the divergence term), internally generated entropy (e.g., trajectory drift due to localized GPS loss of accuracy) and negative entropy inputs. It is closely related to equations for the thermodynamic entropy dynamics of weather.

Weather is a large source of entropy for air traffic management from an information theory viewpoint, and improvements in both tactical and strategic weather prediction, and hyper-local weather prediction; would enable higher-capacity safe air-space operations. From a thermodynamic perspective, the energy radiated from the Sun to Earth is high temperature, low entropy, and concentrated on the equatorial regions. The Earth then radiates this energy back to space as low temperature, high entropy, and dispersed black body radiation. This process is mediated by the general atmospheric circulation – in other words, tropospheric weather – which generates large amounts of thermodynamic entropy (22x as much as the energy received from the Sun). Moreover, this process can be highly chaotic[5]. The information entropy induced by weather's high thermodynamic entropy and chaotic attractors is very high.

B. Air Traffic phases

Analogous to matter, traffic can exist in different phases, characterized by different levels of entropy. The highest levels of entropy are traffic jams, whose governing equations are similar to supersonic shock waves. Analogues to gas, liquid, and solid are described in a subsequent section. It should be noted that many compounds have far more than three distinct phases (e.g., at least ten for water), with complex phase diagrams. These basic four analogues – shock wave, gas, liquid, and solid - are just a starting point. The safe capacity of the airspace is dependent on air traffic phases. Air traffic phases are primarily determined by design of air traffic systems and implemented through command and control of aircraft trajectories, whether through centralized ATM, vehicle-to-vehicle co-ordination, or precise individual vehicle control such as trajectory based operations.

C. Safety and Near Mid-Air Collision (NMAC)

When the motion of aircraft relative to each other is uncontrolled, collisions and near mid-air collisions result. This uncontrolled relative motion can be approximated as Brownian motion of particles, in a series of papers dating back to Graham-Orr, with a starting point being the kinetic theory of particles. NMAC is strategically managed through airspace design (e.g., partitioning airspace vertically and horizontally) and through ATM controlling air traffic phases. Tactical avoidance of NMAC is accomplished by re-vectoring aircraft prior to NMAC – either through ATC commands, TCAS, or ACAS-X. In Brownian motion of particles, the re-vectoring occurs after elastic collisions between particles. Fortunately for aircraft, the revectoring usually occurs prior to collision through vehicle-to-vehicle see and avoid, or through ATM conflict detection and resolution. The rate at which re-vectoring occurs is modeled through Brownian motion collision.

D. Information Physics - Negentropy

The disorderly processes contributing to entropy are counterbalanced by information flows in the form of ATC command and control and vehicle-to-vehicle co-ordination. The term negative entropy (later shortened to negentropy) was introduced by the statistical mechanics/quantum physicist Erwin Shrodinger[7]. Information flows can provide negative entropy. The communications from air traffic control modify probability distributions related to separation. The effectiveness depends on factors such as the variable time delay between a pilot receiving an amended clearance (e.g., climb to flight level 3500, proceed direct to initial approach fix) and then executing the amended clearance (e.g., with a variable time delay of ten to fifty seconds). This variable time delay is in essence a noisy communication channel. The time delay also affects the controllability of the system.

In 1867 James Clerk Maxwell, one of the founders of statistical mechanics, proposed a thought experiment: a 'Maxwell demon' that sorts high energy and low energy gas particles by closing and opening a trap door in a partitioned container as gas molecules come by; eventually one partition of the container has the high energy gas molecules and the other partition low energy gas molecules. Maxwell's demon is a negentropy pump who decreases overall entropy of the system it is managing. In subsequent developments, it was determined that the computation and sensing required for Maxwell's demon required at least as much energy as the decrease in entropy, resolving the apparent paradox of a thermodynamic perpetual motion machine. Experimental versions of Maxell's demon as applied to thermodynamics have been recently reported[8] As expected, the energy required for sensing and computation exceeded the amount of energy that could be extracted through the negative entropy.

Maxwell's demon became an early model for measuring the workload of Air Traffic Controllers[8]. Specifically, Sporn developed a model based on macro-states and micro-states from statistical mechanics in which the airspace is partitioned into small cubes the size of separation distance required between aircraft. The difference in entropy between random distributions of aircraft and distributions in which no two aircraft occupied the same cube was used to measure the workload of Air Traffic Controllers providing separation assurance.

Generalizing, the difference in entropy between distributions of aircraft trajectories that are safe versus those distributions that arise in uncontrolled airspace and lead to collisions is a lower bound on the command and control information flow required from air traffic control.

E. Integration with other probabilistic approaches to analysis and design of ATM:

From a numerical viewpoint, entropy has a number of favorable properties as a calculus for uncertainty, such as additive composition of the entropy of statistically independent systems. The logarithm essentially converts convolution of probability distributions to addition. Standard probability distributions used in air traffic analysis, such as uniform and Gaussian distributions, often readily convert to entropy:

Entropy of a uniform distribution on N discrete events each with probability 1/N = log N

Non-uniform distributions over N events are always less than log N. If one of these events occurs with probability 1, then the entropy is 0.

Entropy of a Gaussian distribution with variance (where *v* is the variance):

$$S = \frac{1}{2}(1 + \log(2\pi v^2)) \tag{4}$$

After the traffic management crisis in 1968, a number of studies were done which advocated queuing theory analysis of air traffic services[9]. Poisson models can be converted to entropy-based calculations, although upper and lower bounds need to be used since the entropy of a poisson process is not analytic.

On a deeper level, the formulation of entropy as an aggregate statistic on probability distributions is tightly coupled with a large volume of work on statistical mechanics and information theory. Pseudo-conservation laws and bounding constraints provide traction for design analysis of air traffic management at an aggregate level of abstraction. Wide portions of the design space that are infeasible can be excluded from more detailed consideration, enabling a top-down hierarchical refinement of designs for future ATM.

Conversely, the results from detailed probabilistic analysis of narrow aspects of air traffic control, such as Detect and Avoid analysis for UAS that yield fine-grained probability distributions, can be lifted up to the level of aggregate entropy to provide tighter bounding constraints in entropy calculations and simulations.

F. Maximum Entropy approach:

One of the difficulties in doing probabilistic design and analysis of ATM is obtaining probability distributions either from incomplete statistical evidence or from simulations that have not been fully calibrated across their range. For the design of future heterogeneous airspace a generation from now, where the vehicles and traffic flows are not known accurately, this is particularly challenging.

The Principle of Maximum Entropy states that when one searches for a probability distribution p that satisfies some constraints (evidence), the correct one to choose is the one that maximizes the entropy subject to these constraints. The maximization constraint is typically solved using lagendrian multipliers.

" ...in making inferences on the basis of partial information we must use that probability distribution which has maximum entropy subject to whatever is known. This is the only unbiased assignment we can make; to use any other would amount to arbitrary assumption of information which by hypothesis we do not have."

Jaynes showed that the principle of maximum entropy could yield the same basic equations for statistical mechanics – such as the partition function – as derivations based on assumptions over large numbers of particles. This provides an avenue for applying mathematics from fields such as statistical mechanics to small numbers of vehicles (e.g., much smaller than Avogrado's number) without resorting to approximations that are based on distributions over large populations.

III. Anticipatory Merging

As an example of high capacity but safe traffic control algorithms that can be adapted to aviation from automotive Co-operative Adaptive Cruise Control, we present an enhancement to MIT's bilateral control[3]. This model is being used to refine and validate the entropy-based mathematical model in this paper.

The suseptability of vehicular traffic under manual control to traffic jams is an everyday experience to a significant portion of commuters. Traffic jams are a type of kinetic wave, which have characteristics such as persistence long after a disturbance has passed, and propagation backwards through the traffic flow. In aviation, fixed wing aircraft don't brake, but they do the equivalent – entering holding patters. In the summer of 1968, traffic at the five busiest airports got to the point where planes were stacked up in holding patterns ten thousand feet or more. A geometric model for kinetic waves is presented below from Lighthall[10]

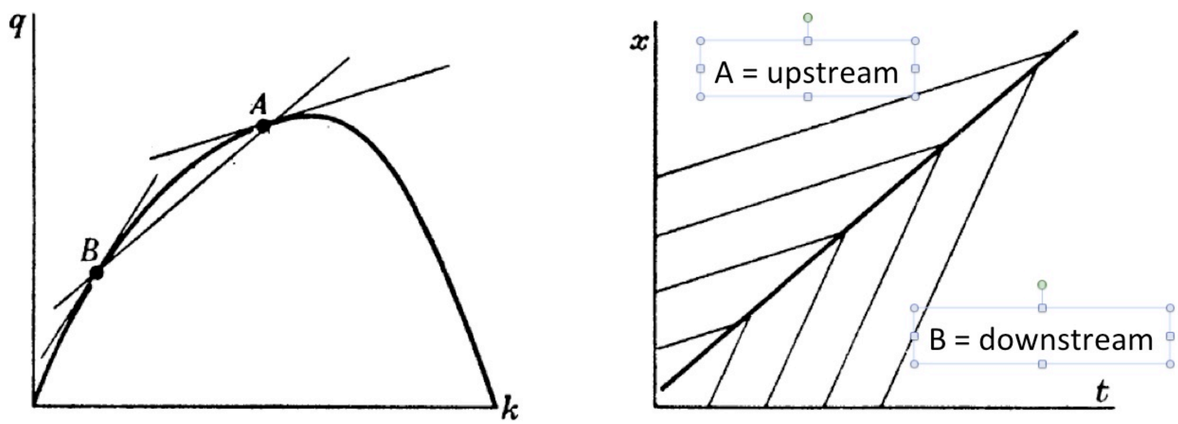

Figure 1: Geometric model for kinetic waves.

On the left of figure 1 is a plot of throughput capacity versus traffic density. As the density exceeds the peak throughput level, the vehicles from behind slow down due to narrowing distance below safe separation with the vehicles ahead. The phenomena is the same as supersonic shock waves. This can occur due to random events, such as a nervous driver putting on the brakes in an otherwise calm traffic situation, or more usually due to merging or lane closure for an accident. As the vehicles reach the front of the traffic jam, they can once again accelerate. This is point A, upstream of the traffic jam. Point B is downstream of the traffic jam. On the right is the line connecting the upstream tangents and the downstream tangents – this is the kinetic wave. Traffic Flow Management was implemented after summer of 1968 to ensure that arriving traffic stayed to the left of the peak for the right side of figure 1. In effect, the holding pattern was pushed back to the departure airport.

Autonomous automobiles that implement Adaptive Cruise Control algorithms that mirror human manual control are subject to the same traffic jams as human drivers. Figure 2 is a snapshot of a simulation of unilateral control as defined in reference 3, which is what is essentially implemented on (forward) Traffic Aware Cruise Control algorithms available in production vehicles today. The simulation is of an infinite loop that enters the top left, and loops from the top right down to the left of the next row, and so on to the bottom right whereupon it loops back to the top left. The clumping of automobiles is evident, and in the dynamic simulation kinetic waves (traffic jams) arise and propagate backwards.

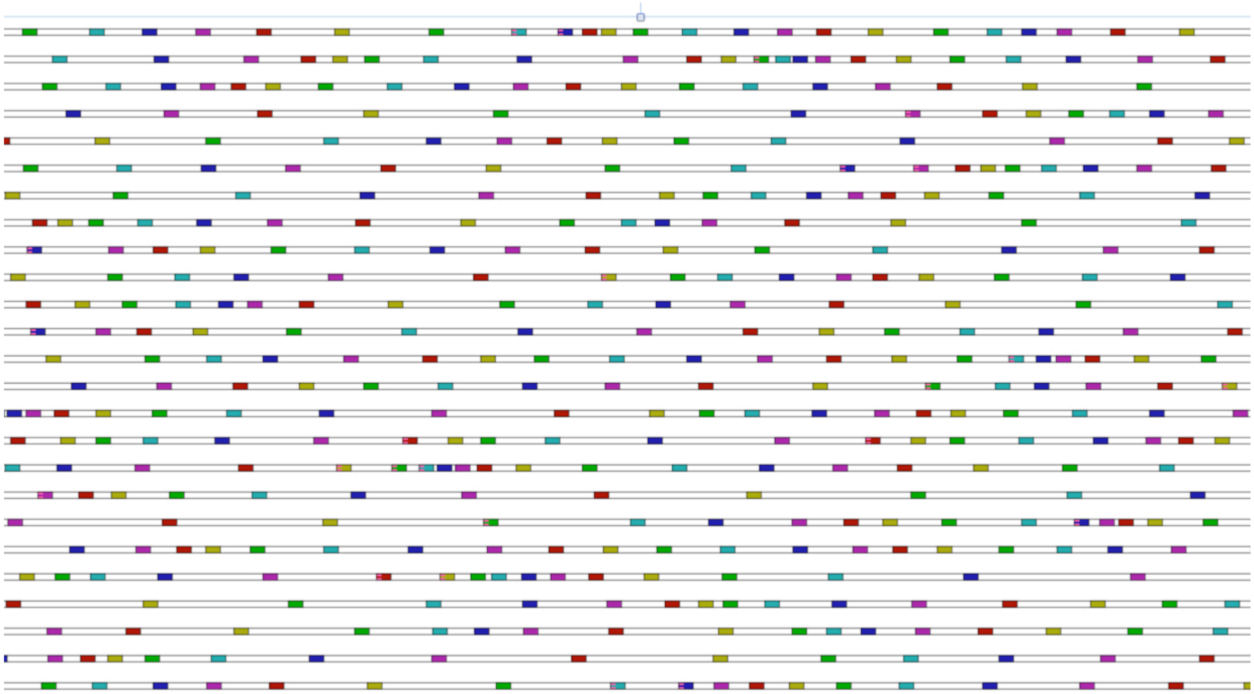

Figure 2: Traffic clumping and traffic jams resulting from standard Adaptive Cruise Control (Unilateral Control)

Using the vehicle distribution in figure 2 as a starting point, then bilateral control is applied. Bilateral control communicates with the vehicle behind as well as sensing the vehicle ahead, and applies acceleration and deceleration longitundanally to balance forward and backward relative distances and relative velocities. The result after a short period of time is that traffic clumps have been smoothed out. There are a number of complementary explanations for the removal of suseptability to traffic instabilities. The first is that the bilateral control algorithm introduces delays that buffers traffic locally from instabilities that get close to the critical threshold where kinetic waves start to form. The second explanation, noted in reference 3, is that by using independent forward and backward feedback control channels but with both having reduced gain, neither one has a gain near unity and hence both control loops are damped. The third explanation, which is described qualitatively in reference 3, is the bilateral control algorithm 'cools' the traffic from a gaseous phase to a liquid phase and finally a solid phase where the vehicles proceed in fixed relation to each other. This analogy to thermodynamic phases of matter dependent on temperature becomes more precise when the entropy is formulated on probability distribution for relative distance. The bilateral control algorithm removes entropy from the system by stabilizing relative distances. When disturbances are introduced, for example as would occur in aviation when planes encounter adverse weather such as clear air turbulence, the traffic first starts to clump and then smooths out again.

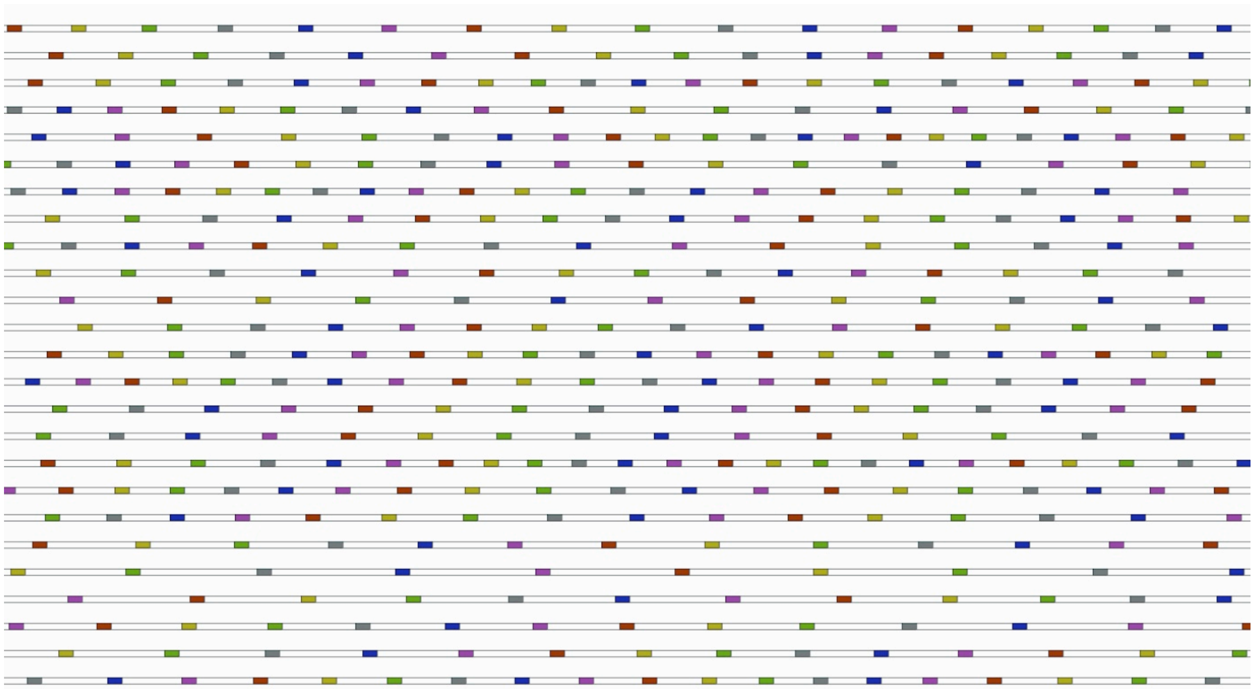

Figure 3: Removal of traffic instabilities through Bilateral Control

Figure 4 shows our enhancement to bilateral control – anticipatory merge. Traffic flows from PDX and LAX heading east merge at an intersection over Kansas City. Before merging over Kansas City, they 'see' the traffic on the other leg as ghost vehicles that interact under the same bilateral control algorithm. By the time the actual merge occurs, they aircraft are appropriately spaced. This provides some of the same benefits of ATD sequencing through speed reductions before meter points at arrival gates. However, the number of small adjustments is greater. There are two advantages. First, when there are disturbances, the bilateral algorithm integrates the traffic smoothing into the ongoing minute accelerations and decelerations between planes. The second advantage is that as the volume of traffic increases, the more distributed bilateral control algorithm scales better.

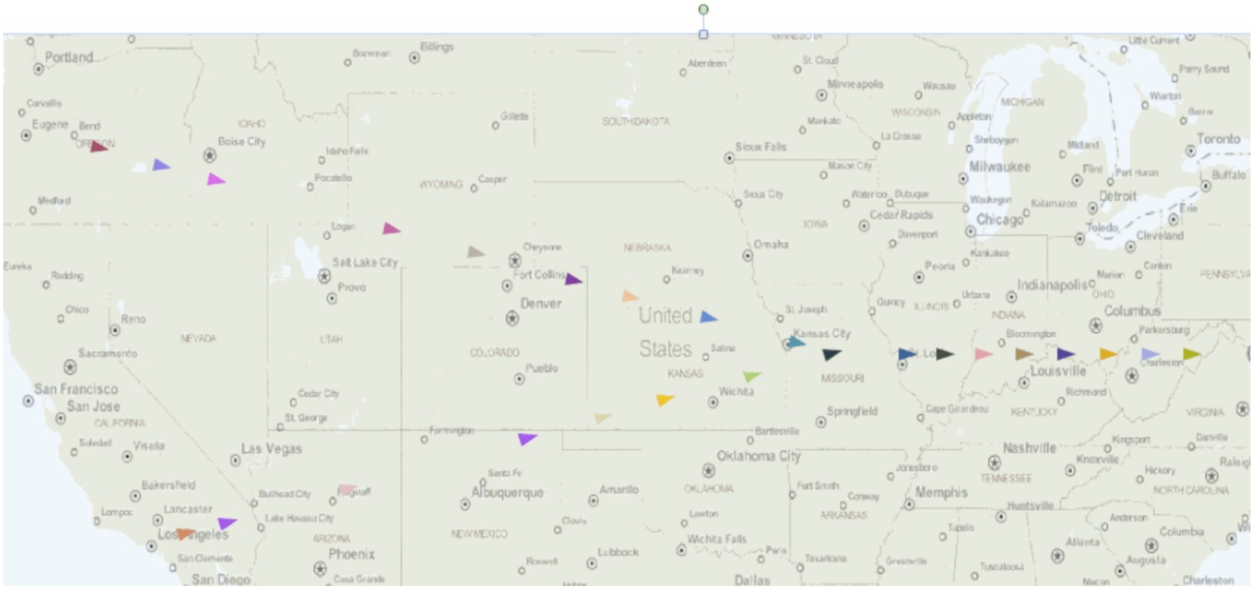

Figure 4: Anticipatory Merge with Bilateral Control

The entropy management principles developed in this paper apply to both centralized control and decentralized control. The distinction is whether there is one Maxwell Demon or many Maxwell Demons.

IV: Conclusion

This paper has presented design principles for 2035 and beyond Air Traffic Management that are applicable across a wide range of scenarios for fuure air space usage. The principles anticipate that autonomy technology will lead to significantly more heterogeneous air space usage, with the potential for much greater density while still requiring a high degree of safety. The underlying principle is to design from the beginning to manage entropy, by balancing the processes that lead to disorder with negative entropy flows principally in the form of air traffic management command and control, realized either centrally or through distributed capabilities including vehicle to vehicle. The paper presents mathematical constraints, both for statics and dynamics. One of the hypothesis of the paper is that there will be future cross-over of technology for traffic management for autonomous cars (co-operative adaptive cruise control) to traffic management technology for aviation. An example of this potential was presented based on recent work at MIT for bilateral control.

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Acknowledgments

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