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Empirical exploration of air traffic and human dynamics in terminal airspaces

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ABSTRACT

We propose a multi-layer network approach to model and analyze air traffic terminal networks, which are viewed as complex, task-critical, techno-social systems with numerous interactions among airspaces, procedures, aircraft, and air traffic controllers (ATCOs). *Route-based Airspace Network* (RAN) and *Flight Trajectory Network* (FTN) are developed to represent critical physical and operational characteristics. *Integrated Flow-Driven Network* (IFDN) and *Interrelated Conflict-Communication Network* (ICCN) are formulated to represent air traffic flow transmissions and intervention from ATCOs, respectively. Furthermore, a set of analytical metrics, including network variables, complex network attributes, controllers' cognitive complexity, and chaos metrics, are introduced and applied in a case study of Guangzhou terminal airspace. Empirical results show the existence of fundamental diagram and macroscopic fundamental diagram at the route, sector and terminal levels. Moreover, the dynamics and underlying mechanisms of "ATCOs-flow" interactions are revealed and interpreted by adaptive meta-cognition strategies based on network analysis of the ICCN. Finally, at the system level, chaos is identified in the conflict system and human behavioral system when traffic switches to the semi-stable or congested phase. This study offers analytical tools for understanding the complex human-flow interactions at potentially a broad range of air traffic systems, and underpins future developments and automation of intelligent air traffic management systems.

1. Introduction

Worldwide ATM system is undergoing the process of upgrading and transformation to cope with increasing air traffic demand and congestion, especially in high-density airports and terminal airspaces. Within the strategic planning of ATM systems like SESAR, NextGen and ASBU, numerous advanced operational concepts, such as "ATM Network Management", "User Driven Prioritization Process", "Flow Contingency Management" and "Complexity Management", are proposed to enhance the system-wide performance and confine the propagation of congestion. Air traffic systems are typical examples of complex techno-social systems, where effective management requires a thorough understanding of the relationship between infrastructure and human behavior (Monechi et al., 2015). In order to develop and deploy high-level operational concepts and automation systems, it is essential to conduct an in-depth investigation of the intrinsic air traffic dynamics,

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Nomenclature

AFR	Average Flow Rate
ASBU	Aviation System Block Upgrades
ATCO	Air Traffic Controller
ATV	Average Traffic Volume
CL	Communication Load
CSN	Conflict Situation Network
EAD	Equivalent Average Density
EAS	Equivalent Average Speed
FTN	Flight Trajectory Network
ICCN	Interrelated Conflict-Communication Network
ICN	Interventional Communication Network
IFDN	Integrated Flow-Driven Network
NextGen	Next Generation Air Transportation System
OFP	Operational Flight Path
RAN	Route-based Airspace Network
SESAR	Single European Sky ATM Research
SFP	Standard Flight Path
SSPC	Solution Space-based Perceived Complexity

by revealing temporo-spatial air traffic characteristics and uncovering the intrinsic "human-flow" (i.e. ATCO-aircraft) interactions.

Flow congestion is one of the key manifestations of air traffic dynamics (Hu et al., 2013). Nevertheless, studies on the generation, accumulation, propagation, and dissipation of air traffic congestion are not widely reported. Delay has been studied as a key performance indicator of airspace capacity since the 1940 s (Bowen and Pearcey, 1948; David et al., 1998). The classic exponential relationship between capacity utilization and delay presents the most fundamental relationship between demand and supply, and has guided ATM research for decades that followed (FAA, 1983). Some recent findings suggest refined demand-supply relationship at airports based on empirical data (Ezaki and Nishinari, 2014; Simaiakis et al., 2014), which underpins novel control strategies for congestion mitigation. In order to capture the spatial effect of congestion, delay propagation models receive increased attention. Single flight delay is modelled using time-based petri network to analyze the chain reaction (Li and Ding, 2008), and provides the basis for flight delay prediction and alert (Xu et al., 2009). Furthermore, mechanisms of the emergence and accumulation of delays in airport networks are studied based on multi-flight delay model (Hau et al., 2007) and analytical econometric approach (Kafle and Zou, 2016).

The flow dynamics of road traffic have motivated many air traffic flow models in recent years, in order to predict the aggregate effect on air traffic delays and to support large-scale flow management. Bayen et al. (2006) introduce a partial differential equation approach (Lighthill and Whitham, 1955) for the prediction and control of air traffic flow propagation along one-dimensional air routes in National Airspace Networks. Inspired by the cell transmission model (CTM) of vehicular traffic (Daganzo, 1994), 1D (Menon et al., 2004) and 2D (Menon et al., 2006) cell-based models are derived by discretizing relevant partial differential equations. Building on the models of Menon et al. (2006), Large-capacity CTM is proposed by Sun and Bayen (2008) and Wei et al. (2013) to model large-scale air traffic networks by distinguishing link and cell levels for each flight path. Cao and Sun (2011) develop a Link Transmission Model without discretization on the cell level to improve computational efficiency. Zhang et al. (2014) propose a CTM-based flow model for terminal airspace, via a hypothesized "flow-density-velocity" relationship (or the fundamental diagram, see Kerner, 2009) of terminal air traffic. The primary focus of the abovementioned studies is the control of air traffic based on airspace or route capacity, with little attention given to the empirical validity of the hypothesized flow-density-velocity relationships, which play a vital role in the aggregate behavior of air traffic and are essential to the effectiveness of such controls.

With the increased workload of ATCOs, significant efforts have been devoted to the modeling and analysis of human dynamics. Odoni et al. (1997) categorize ATCOs' behavioral models into macroscopic and microscopic levels. Macroscopic models are high-level analytical models that analyze individual ATCO's performance by establishing input-output transfer mechanisms, treating the internal information process as a black box. Examples of this type include workload model (Farmer et al., 2003), crossover model for manual control tasks (McRuer and Jex, 1967) and human response delay model (Ren and Clarke, 2005). On the other hand, microscopic models attempt to describe the cognitive processes (e.g. attention resource assignment, memory usage, situation awareness, decision making and monitoring) in greater granularity and detail; examples include CT-ATC (Kallus et al., 1999), MoFL (Eyferth et al., 2003), and Apex (Lee et al., 2005). The quantitative modeling of ATCOs' behavioral dynamics sheds light on the fundamental rules that human follow when executing tasks, and provides tools to refine traditional flow-based air traffic modeling. Wang et al. (2013) propose an empirical method to study ATCOs' high-level dynamics by analyzing their communication intervals, and suggest that the distribution of communication intervals follows the power-law distribution. A follow-up study (Wang et al., 2016) introduces a network approach to the